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Goal-directed simulation of past and future events: Cognitive and neuroimaging approaches

A dissertation presented

by

Katrin Daniela Gerlach

to

The Department of Psychology

in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Psychology

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Cambridge, Massachusetts

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Advisor: Professor Daniel Schacter Author: Katrin Daniela Gerlach

Goal-directed simulation of past and future events:
Cognitive and neuroimaging approaches

Abstract

Goal-directed episodic simulation, the imaginative construction of a hypothetical personal event or series of events focused on a specific goal, is essential to our everyday lives. We often imagine how we could solve a problem or achieve a goal in the future, or how we could have avoided a misstep in the past, but many of the behavioral and neural mechanisms underlying such goal-directed simulations have yet to be explored. The three papers of this dissertation investigated the neural correlates of three types of future episodic simulations in Papers 1 and 2 and examined a fourth such simulation directed at past events as an adaptive, constructive process in Paper 3. Some research has associated default network activity with internally-focused, but not with goal-directed cognition. Papers 1 and 2 of this dissertation showed that regions of the default network could form functional networks with regions of the frontoparietal control network while participants imagined solving specific problems or going through a sequence of steps necessary to achieve a personal goal. When participants imagined events they associated with actually attaining a goal, default network regions flexibly coupled with reward-processing regions, providing evidence that the default network can join forces with other networks or components thereof to support goal-directed episodic simulations. Using two distinct paradigms with both young and older adults, Paper 3 focused on episodic counterfactual simulations of how past events could have turned out differently and tested whether counterfactual simulations could affect participants' memory of the original events. Our results revealed that episodic counterfactual simulations can act as a type of internally generated

misinformation by causing source confusion between the original event and the imagined counterfactual outcome, especially in older adults. The findings of the three papers in this dissertation lay the groundwork for further research on the behavioral and neural mechanisms of goal-directed episodic simulations, as well as their adaptive functions and possible downsides.

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Introduction

Imagine the following: While eating your breakfast on a typical morning, you are thinking about some recent past and upcoming future events in your life. You just noticed that the fridge is rather empty and imagine how you will have to drive to the supermarket later on, collect all the items you will need for the following week amongst many other shoppers, and wait in line to pay. You cheer up when you realize that a week from now, you will have arrived in Hawaii, where you will be able to go hiking and swim in a pool. You check your watch and notice that you have to leave for work soon – you are dreading facing one particular coworker. If you had only been a little more diplomatic in a dispute over a project yesterday, it could have ended very amicably. Instead, you will need to stop by the desk and apologize today; you spend some time imagining different ways in which you might do so given your past experiences with this coworker.

Thought processes such as these are ubiquitous (Berntsen & Jacobsen, 2008; D'Argembeau, Renaud, & Van der Linden, 2011; Klinger & Cox, 1987; Smallwood & Schooler, 2006; Taylor & Schneider, 1989) and give us the fascinating and likely unique ability to plan and pre-experience future events, imagine desired goals and solutions to problems, and simulate alternative outcomes to past events (Buckner & Carroll, 2007; Gilbert & Wilson, 2007; Kahneman & Miller, 1986; Schacter, Addis, & Buckner, 2007; Suddendorf & Corballis, 2007). Episodic simulation, the *imaginative construction of a hypothetical personal event or series of events* (Schacter, Addis, & Buckner, 2008; Taylor & Schneider, 1989), involves mental imagery, tends to be directed toward a specific personal goal or problem, and allows an individual to project him- or herself into an alternative past or a hypothetical future scenario. Children appear

to develop such prospection capabilities over the preschool period when they learn to anticipate future needs (e.g., McCormack & Atance, 2011).

There are many simulation processes that do not necessarily involve imagining personal episodes or events, such as simulations of the mental states of others or of spatial navigation (e.g., Buckner & Carroll, 2007; Goldman, 2006; Spreng, Mar, & Kim, 2009), for which I will use the broader term 'mental simulations' in the following. Even though mental imagery and cognitive processes engaged in planning have received considerable empirical attention (e.g., Hayes-Roth & Hayes-Roth, 1979; Kosslyn, 1996; Miller, Galanter, & Pribram, 1960; Morris & Ward, 2005), episodic simulations have only recently spurred a vigorous research effort, leaving many of its cognitive and neural mechanisms yet to be explored. The diverse benefits of investigating episodic simulations range from improving our understanding of their adaptive functions as well as potential drawbacks, to allowing us to harness them most effectively in the service of goal attainment, well-being, and treatment of clinical disorders, to adding a novel perspective on the existing literature on planning. In addition, research on the cognitive neuroscience of episodic simulations will advance our knowledge of how different brain networks interact under simulation conditions. It will allow us to identify the neural mechanisms behind specific features of episodic simulations and to forge new theoretical insights into the function of these networks and their different components.

This dissertation consists of three papers that investigate cognitive and neural processes underlying goal-directed aspects of mental simulations of both past and future events. The use of the term "goal-directed" refers to episodic simulations that are not only internally focused and self-referential, but also imply a clear purpose or goal. A goal-directed episodic simulation could involve envisioning a solution to a current or anticipated future problem (Schacter et al., 2008),

constructing a personal plan, fantasizing about achieving a desired goal, or imagining how a failed goal could have been reached in order to be able to attain it in the future. Some goal-directed simulations are likely to engage executive processes that allow an individual to keep in mind the desired goal, integrate and relate potentially complex information, and make decisions about how to overcome an obstacle or proceed with a plan. Others may focus on affective and reward-related facets of future goals and give an individual the ability to pre-experience what it would feel like to attain a goal or to compare different hypothetical outcome scenarios. In such goal-directed episodic simulations, the individual functions as a "cognitive-affective agent" (Christoff, Cosmellil, Legrand, & Thompson, 2011) who addresses the problem or goal that motivated the simulation. Unlike spontaneous daydreams or impossible fantasies, goal-directed simulations are constrained by their function and focus.

Social and clinical psychology research has revealed just how critical the pursuit of personal goals is to our well-being (e.g., Wiese, 2007): Individuals pursuing subjectively important personal goals have been found to report significantly higher well-being than individuals without such goal-directedness who tend to recount a lack of meaning and structure in their lives and score lower on measures of self-worth (e.g., Emmons, 1986; Freund & Baltes, 2002; Klinger, 1977; Park, Crocker, & Kiefer, 2007). Further research has revealed that not only the successful achievement of a goal, but even the process of working toward a goal, especially when carried out with the necessary flexibility, represents a rewarding experience (e.g., Brandtstätter & Rothermund, 2002; Brunstein, 1993; Emmons, 1996; Riediger & Freund, 2004). In the aging literature, the pursuit of personal goals relevant to the elderly individuals' personal development and their own as well as others' future well-being has been linked to subjective happiness (Lapierre, Bouffard, & Bastin, 1997). Irrespective of their ability to attain personal

goals, patients suffering from clinical depression have been shown to have difficulties setting goals for themselves (Street, 2002). In contrast, patients with bipolar disorder often pursue an excessive number of personal goals during manic phases, a symptom that appears to be triggered by the accomplishment of an initial significant life goal (S. L. Johnson, 2005). The relevance and rewarding nature of goal pursuit is also apparent in the vast self-help literature concerned with goal setting, motivation, and goal achievement (e.g., Dyer, 1989; V. Johnson, 2006; Tracy, 2002). Computer gaming companies have also taken advantage of this phenomenon and keep many players engaged and addicted to their games by consistently providing them with in-game goals to pursue and accomplish (e.g., Malone, 1982).

Despite the important role that goals play in our lives, relatively little empirical attention has been paid to goal-directed simulations. However, various areas of psychology have examined mental simulations in the context of emotion and behavior regulation (e.g., Rivkin & Taylor, 1999; Taylor & Schneider, 1989), decision-making (Miller et al., 1960; Suddendorf & Bugsby, 2005), learning (Feltz & Landers, 1983; Kahneman & Miller, 1986; van Meer & Theunissen, 2009), and prospective memory (Brewer & Marsh, 2010). For instance, mental simulations have been shown to reduce relapse rates in addicts who imagine themselves in tempting future situations and rehearse strategies to avoid smoking or drinking (Brownell, Marlatt, Lichtenstein, & Wilson, 1986; Marlatt & Gordon, 1985). Mentally simulating critical future situations can also benefit athletes' subsequent performance when they imagine themselves returning their opponent's challenging tennis backhand or kicking the soccer ball during a penalty shootout (Feltz & Landers, 1983). In the clinical literature, imagining a stressful event and the emotions associated with it has been shown to have similarly beneficial effects on stress reduction, affect improvement, and the initiation of problem-solving activities as talking or writing about them

(Rivkin & Taylor, 1999). *Counterfactual simulations* of how past events could have turned out differently can aide overcoming stressful and traumatic experiences (Lazarus & Folkman, 1984; Meyer & Taylor, 1986; Taylor, 1983), regulating emotions (Epstude & Roese, 2007; Wrosch, Bauer, & Scheier, 2005), and learning from past mistakes (Kahneman & Miller, 1986).

Some mental simulations have also been shown to facilitate the link between goals and actions (Miller et al., 1960; Hayes-Roth & Hayes-Roth, 1979; Taylor & Pham, 1996). Taylor and Pham (1996) have distinguished between simulations that involve visualizing a desired *outcome* and pre-experiencing the positive feelings associated with the goal state, and so-called *process simulations* that detail the steps required to attain a goal or solve a problem. When comparing the effectiveness of these simulations with regard to the goal of obtaining a good grade on an exam or assignment, they found that those students who engaged in process simulations of the steps they should take to achieve the goal began studying earlier, spent more time studying, were more accurate in their estimations of how long it would take them to complete a project, and obtained better grades than those students who repeatedly imagined what it would be like to receive an A (Pham & Taylor, 1999; Taylor, Pham, Rivkin, & Armor, 1998). Process and outcome simulations are likely to engage distinct mechanisms to bring about behavior: Outcome simulations should make people desire a goal more, whereas process simulations should facilitate actual goal-directed behavior by outlining the specific steps necessary to achieve the goal.

However, there is evidence that outcome simulations can also promote desired behavior in certain contexts. If participants in a study on healthier eating, who were inclined to be motivated by positive messages, imagined the personal benefits of eating more fruits and vegetables, they consumed 20% more fruits and vegetables during the following week (Spiegel,

Grant-Pillow, & Higgins, 2004). The simulation manipulation was equally effective for participants who responded better to preventative measures and imagined the potential negative personal consequences of not eating enough fruits and vegetables. In another study on healthier lifestyle changes, inactive individuals were more motivated to engage in physical activity and exercised more over a month-long period if they imagined their future selves as being stronger, happier, and more energetic (Chan & Cameron, 2012). Here, imagining the goal state was more effective than simulating the steps toward enacting the desired behavior (e.g., getting home after work, putting on sports clothes, driving to the beach to go for a walk). Other studies have also found an increase in participants' motivation to work toward solving a problem or to pursue a goal, as well as a decrease in their anxiety about being able to achieve a goal when participants engaged in positive simulations of a desired outcome (e.g., Brown, MacLeod, Tata, & Goddard, 2002; Oettingen, 1996; Oettingen & Mayer, 2002; Taylor & Pham, 1996). These characteristics of outcome simulations may have contributed to the results of a study by Spreng and Levine (in press), where participants imagined a number of personal future events, and the researchers tracked their occurrence one year later. Even though participants were not specifically instructed to imagine desired future outcomes, they were asked to simulate highly likely events in response to cue words, many of which could presumably be categorized as personal goals (Spreng & Levine, 2006). The authors found that 59-64% of the imagined personal future events had been enacted.

Outcome simulations have also been shown to benefit far-sighted decision-making. By allowing individuals to pre-experience a future event's affective impact, outcome simulations can attenuate temporal discounting, a bias toward choosing more immediate over higher-valued delayed rewards (Benoit, Gilbert, & Burgess, 2011; Peters & Büchel, 2010a). When participants

were presented with immediate and delayed rewards and imagined events that receiving a reward would allow them to experience, they were more likely to overcome any temporal discounting bias than if they simply viewed the reward amount and delay (Peters & Büchel, 2010a) or provided a semantic estimate of what the reward could purchase (Benoit et al., 2011). The existing research on goal-directed simulations has demonstrated some of the differential benefits of outcome and process situations, but many aspects of goal-directed simulations have yet to be explored (for review, see Schacter, 2012). This dissertation is designed to examine further the cognitive and functional characteristics of such goal-directed simulations in addition to identifying their neural bases.

The cognitive neuroscience of episodic simulation

The recently emerging literature on the cognitive neuroscience of episodic simulation can be traced back to the discovery that remembering past and imagining future events rely on a shared neural network, the default network (Addis, Wong, & Schacter, 2007; Botzung, Denkova, & Manning, 2008; Okuda et al., 2003; Szpunar, Watson, & McDermott, 2007). This network of interconnected brain regions, including medial prefrontal cortex, lateral and medial temporal lobe, as well as posterior regions such as the inferior parietal lobule, posterior cingulate, and retrosplenial cortex (Buckner, Andrews-Hanna, & Schacter, 2008, Gusnard & Raichle, 2001), support both episodic memory and future simulation. This discovery has lead to the hypothesis that we construct and flexibly recombine memories of previous experiences to be able to imagine future events (Schacter & Addis, 2007). Further evidence in support of this hypothesis has come from amnesic patients with the similarly impaired ability to remember personal past and to simulate personal future events (Hassabis, Kumaran, Vann, & Maguire, 2007; Tulving, 1985), though not all amnesics have been shown to have impaired future imagining (Squire et al., 2010).

Clinical populations who struggle to generate detailed autobiographical memories also tend to have parallel deficits in generating detailed future episodes (D'Argembeau, Xue, Lu, Van der Linden, & Bechara, 2008; Williams et al., 1996).

The simulation of personal future events in the early neuroimaging paradigms tended to lack goal-directed aspects of episodic simulation. Instead, participants typically imagined plausible future events in response to cue words or phrases without a specific goal or purpose in mind (e.g., Addis et al., 2007; Spreng & Grady, 2010; Szpunar, Chan, & McDermott, 2009; Szpunar et al., 2007). For instance, if participants in these paradigms received the cue word "family" for an episodic future simulation, they were not prompted to imagine planning their next family reunion or envision how they could resolve a conflict with a family member but were free to construct any kind of future scenario involving their family. Other paradigms only provided participants with open-ended, unconstrained instructions to think about the near or far future (Okuda et al., 2003) or asked them to recombine elements of past experiences (Addis, Pan, Vu, Laiser, & Schacter, 2009). While all of these studies placed an emphasis on inventing future events that contained certain elements or involved a prescribed theme, no specific task, function, or purpose was attached to these future scenarios. Andrews-Hanna, Reidler, Huang, and Buckner (2010) sampled participants' spontaneous task-unrelated thoughts, which are likely to have included goal-directed thoughts regarding future plans or obstacles, but participants were not specifically directed to engage in such thoughts. A decision paradigm in which participants were required to simulate personal future events in order to answer questions about them came closest to prompting participants to engage in goal-directed simulations (Andrews-Hanna, Reidler, Huang, et al., 2010). In all of these early paradigms, participants had to turn their attention inward and imagine self-referential scenarios, which reliably engaged the default network.

However, as discussed earlier, goal-directed simulations also rely on cognitive control to keep in mind the desired goal, coordinate sequences of events, or make decisions on how to proceed.

Motivations behind the three dissertation papers

Early studies of the default network had not associated it with goal-directed cognition (Raichle et al., 2001; Shulman et al., 1997). On the contrary, the default network had been labeled a "task-negative" network for its decreased activity during attention-demanding visual tasks relative to passive "baseline" fixation tasks that engaged the default network instead. Subsequent resting-state functional connectivity neuroimaging studies found that the default network was anti-correlated with or antithetical to a "task-positive" network of brain regions termed the dorsal attention network for its association with attention-demanding cognitive tasks (Fox, Corbetta, Snyder, Vincent, & Raichle, 2006; Fox et al., 2005). Based on these studies, the default network was thought to be associated with unconstrained, spontaneous, and internally focused processes, as well as off-task mind-wandering, during which memories were consolidated, brain networks were stabilized, and individuals were able to project themselves into the future, the past, or the viewpoint of others (e.g., Buckner & Carroll, 2007; Buckner & Vincent, 2007; Golland et al., 2007; Golland, Golland, Bentin, & Malach 2008; Mason et al., 2007). It was an open question whether the default network could support internally generated goal-directed cognition, such as planning or problem-solving simulations, which were likely to also rely on brain regions linked to executive function and cognitive control. Paper 1 of this dissertation uses episodic simulations of solutions to future problems to investigate whether this coactivation of default network regions that are typically described as task-negative, and regions of executive function, which are generally linked to task-focused cognition, is possible.

Paper 2 was designed to examine, for the first time, the neural basis of two other kinds of goal-directed simulations: simulations of desired outcomes and simulations of the steps required to reach a personal goal (Taylor et al., 1998). There are many reasons for why it is important to study the cognitive and neural mechanisms underlying these simulations: We often have trouble motivating ourselves to pursue a goal, can take much longer than anticipated to complete a goal, or fail to remember goals we meant to pursue (e.g., Buehler, Griffin, & Ross, 1994; Chasteen, Park, & Schwarz, 2001; Kahneman & Tversky, 1979). As previously discussed, research on the link between goals and action has singled out process and outcome simulations as being able to facilitate goal-directed behavior (e.g., Taylor & Pham, 1996). However, the vast majority of the previous research on planning has focused on deficits in patients with frontal lobe lesions (e.g., Fellows & Farah, 2005; Luria, 1966; Shallice, 1982; Stuss & Benson, 1986) and on executive control and working memory processes involved in complex and often abstract planning tasks not directed at participants' personal goals (e.g., Morris & Ward, 2005; Philips, Wynn, Gilhooly, Della Sala, & Logie, 1999; Shallice, 1982). Another related line of research has been dedicated to how people formulate and remember intentions to perform future actions (e.g., Einstein & McDaniel, 1990, 2005; Gollwitzer, 1999), but has hardly discussed episodic future simulations.

In Paper 2, participants are therefore asked to imagine themselves going through steps toward attaining a goal (process simulations) and to simulate events they associate with achieving a personal goal (outcome simulations). Affective and reward-related processes are predicted to play an important role in outcome simulations, whereas cognitive control mechanisms are predicted to characterize process simulations. The study tests whether both types of goal-directed simulations recruit the default network, and whether default network regions are able to flexibly couple with the frontoparietal control network, a network of regions associated

with cognitive control (e.g., Vincent, Kahn, Snyder, Raichle, & Buckner, 2008) in the case of process simulations, and with reward-processing regions (e.g., Liu, Hairston, Schrier, & Fan, 2011) in the case of outcome simulations. We are also interested in participants' qualitative assessment of the presented goals post-simulation, including their desirability and predicted difficulty of achievement, as possible differences between the process and outcome conditions could highlight implications for subsequent behavior.

While Papers 1 and 2 of this dissertation examine goal-directed simulations of future events, Paper 3 focuses on episodic simulation processes directed at the past. Episodic simulations of past experiences often occur when we have failed to achieve a goal, which tends to trigger counterfactual simulations of how the past event could have turned out differently (Epstude et al., 2008; Roese & Hur, 1997; Roese & Morrison, 2009). Counterfactual simulations provide an opportunity to learn from past mistakes in order to be better equipped to attain similar future goals, a finding that has been demonstrated in the context of romantic rejections, athletic disappointments, and poor exam performance (e.g., Ciarocco, Vohs, & Baumeister, 2010; Markman, McMullen, Elizaga, 2008; Smallman & Roese, 2009). Simulating such "upward" counterfactual simulations of better outcomes to past events tends to elicit feelings of regret or disappointment but allows individuals to quickly form intentions for improved future behavior (e.g., Galinsky & Kray, 2004; Markman et al., 2008; Nasco & Marsh, 1999; Smallman & Roese, 2009). Constructing upward counterfactual simulations of traumatic past events can also help victims re-gain a sense of control and emotional stability when they imagine what they could have done differently (e.g., Meyer & Taylor, 1986; Silver, Boon, & Stones, 1983; Taylor, 1983). "Downward" counterfactual simulations of how past situations could have turned out even worse

tend to trigger feelings of relative satisfaction and relief (e.g., Roese, 1997; Wrosch et al., 2005), allowing individuals to reclaim their emotional composure and move on to new goals.

Although counterfactual simulations can be adaptive in helping us learn from mistakes and be better equipped in the pursuit of future goals, there could be an unexpected downside to imagining alternative outcomes to past events. Previous research on episodic simulations has demonstrated that imagining events can produce illusions or distortions in the experience of one's personal past and future: Episodic simulations of novel events can lead a person to consider the future or past occurrence of the simulated event as more likely (Anderson, 1983; Koehler, 1991; Sherman, Cialdini, Schwartzman, & Reynolds, 1985) or to create a false autobiographical memory of the event (Garry, Manning, Loftus, & Sherman, 1996; Loftus, 2003; Mazzoni & Memon, 2003), especially if it is imagined repeatedly (Goff & Roediger, 1998; M. K. Johnson, 2006). In line with these findings, Szpunar and Schacter (in press) showed that the repeated simulation of everyday future experiences could cause positive and negative events (though not neutral events) to be perceived as more plausible. In contrast, repeatedly imagining alternative outcomes to past events has been reported to decrease their perceived plausibility (De Brigard, Szpunar, & Schacter, in press).

Adaptive constructive processes are defined by their beneficial effects on cognition and behavior, as well as their ability to create biases and distortions under certain circumstances (Schacter, 2012). In Paper 3, we examine episodic counterfactual simulations as an adaptive constructive process and test whether counterfactual thinking can lead to illusions or distortions of recognition memory. No previous study has investigated whether counterfactual simulations of how personal past experiences could have turned out differently can distort memory for those experiences by rendering the counterfactual outcome more salient than the original memory. In

two experiments with both young and older adults, we seek to test our hypothesis that episodic counterfactual simulations can cause source confusion based on internally generated counterfactual misinformation.

As reviewed above, episodic simulations have recently received considerable empirical attention, but there are many cognitive and neural processes underlying these simulations that have yet to be explored. Even though goal-directed simulations are essential to our everyday lives, we are only beginning to understand their various functions, mechanisms, and potential pitfalls. This three-paper dissertation sought to provide further insight into several kinds of goal-directed simulations of both past and future events: problem-solving simulations, process and outcome simulations, as well as counterfactual simulations. Papers 1 and 2 focus on the neural correlates of simulations of future events and aim to elucidate possible interactivity between the default network and other brain regions. Paper 3 examines episodic simulations directed at the past and their possible effects on memory, with the aim of improving our understanding of episodic simulations as an adaptive, constructive process.

Paper 1:

Gerlach, K. D., Spreng, R. N., Gilmore, A. W., & Schacter, D. L. (2011). Solving future problems: Default network and executive activity associated with goal-directed mental simulations. *NeuroImage, 55*, 1816-1824.

Abstract

Mental simulations are often focused on a goal in the future or a problem to be solved. Recent neuroimaging studies have associated mental simulations of the future with default network activity, but the simulations in these studies were not typically directed toward achieving a particular goal. Goal-directed simulation requires cognitive control to maintain information, make decisions, and coordinate abstract action sequences. Therefore, it should recruit not only the default network, but also brain regions of executive function. To investigate whether default network and executive regions can be coactive in the context of goal-directed simulation, we designed a problem-solving task in which participants simulated solving several specific problems in imaginary scenarios while in the MRI scanner. We analyzed brain activity during simulation relative to a semantic elaboration task and found that goal-directed simulation engaged core regions of the default network and executive dorsolateral prefrontal cortex. A functional connectivity analysis with posterior cingulate and dorsolateral prefrontal cortex seeds revealed that activity in these regions was coupled throughout the goal-directed simulation period and associated with a distributed network of other default and executive regions, including medial prefrontal cortex, medial temporal, and parietal regions.

Solving future problems:

Default network and executive activity associated with goal-directed mental simulations

We spend a significant part of our day engaged in mental simulations, which are often focused on a particular goal or a problem to be solved in the future (D'Argembeau et al., 2011; Gollwitzer, 1999). Whether we imagine what to have for lunch, how to spend the next holiday, or how to resolve a dispute with a friend, these everyday simulations are both internally focused and goal-directed. Recent neuroimaging studies have shown that imagining, or simulating, future events, like remembering past events, is associated with activity in the default network (for reviews, see Buckner et al., 2008; Schacter et al., 2007; Spreng et al., 2009).

However, the simulation of future events in these studies was not directed toward achieving a particular goal, even though simulations in everyday life tend to be geared toward a future goal state or a solution to a problem (Schacter et al., 2008). In typical experimental paradigms, participants imagine an event that might plausibly occur in the future in response to cue words or phrases (e.g., Addis et al., 2007; Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Spreng & Grady, 2010; Szpunar et al., 2007, 2009), recombined elements of past experiences (Addis et al., 2009), or open-ended instructions to think about the past and future (Okuda et al., 2003). These experimental paradigms have reliably engaged the default network, as have related studies of even less constrained internally focused and self-referential mental explorations (Andrews-Hanna, Reidler, Huang, et al., 2010; Buckner & Carroll, 2007; D'Argembeau et al., 2005), as well as studies of mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Mason et al., 2007).

The set of interconnected brain regions that make up the default network include medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC), medial and lateral temporal regions,

and the inferior parietal lobule (Buckner et al., 2008; Gusnard & Raichle, 2001). Although the exact neurocognitive functions of all of the network components remain to be investigated, MPFC has been implicated in many tasks involving self-referential processing (Amodio & Frith, 2006; Andrews-Hanna, Reidler, Sepulcre, et al., 2010; D'Argembeau et al., 2007, 2010; Gusnard et al., 2001; Heatherton et al., 2006). PCC has been observed to be the critical connector hub to all regions of the default network and is hypothesized to be crucial to its functional integration (Hagman et al., 2008).

Despite its involvement in various cognitive processes, the default network is perhaps better known for decreases in activity during tasks that demand external attention (Gusnard & Raichle, 2001; Shulman et al., 1997). Activity of the default network has been described as anticorrelated with a "task-positive" network of brain regions whose activity increases during tasks that demand externally focused attention (Fox et al., 2005; Fransson, 2005; Greicius, Krasnow, Reiss, & Menon, 2003). This task-positive network is comprised of dorsolateral prefrontal cortex (DLPFC), the frontal eye fields, inferior precentral sulcus, middle temporal motion complex, and the superior parietal lobule (Fox et al., 2005; Toro, Fox, & Paus, 2008). Anticorrelations between default and task-positive network regions have typically been found in resting state functional connectivity analyses as opposed to connectivity analyses based on task-evoked activity.

There has been an ongoing debate over whether task-positive and default network regions are truly anticorrelated (Fox, Zhang, Snyder, & Raichle, 2009), or whether negative correlations between default and task-positive network regions could be attributed to global signal regression (Murphy, Rasmus, Handwerker, Jones, & Bandettini, 2009). Using a novel statistical approach that adjusted for whole-brain correlations but avoided global time-course

regression, a recent study selected DLPFC, which had been the most active region during a working memory task, and medial frontal cortex, a default network area that had been the most deactivated during said task, and found that DLPFC and medial frontal cortex were the most antagonistic regions of the two networks during rest (Hampson, Driesen, Roth, Gore, & Constable, 2010). Although the exact interpretation of negative correlations remains controversial, the existing evidence of anticorrelations between the default and the task-positive network (e.g., Fox et al., 2005, 2009; Fransson, 2005; Greicius et al., 2003) raises the question of whether it is possible for brain regions from both networks to be coactive, or whether the competitive relationship between the networks prevents any coactivation of both networks or of select regions within those networks.

Goal-directed simulation of solving a problem is not only a prospective, self-referential process (e.g., Addis, et al., 2007), but also requires cognitive control of information. For example, when simulating a future event in which the goal is to resolve a dispute with a friend, it is not sufficient simply to imagine a future scene involving the friend. One must also retrieve and integrate what one knows about a friend's likely response, what kinds of approaches have worked in similar situations, how to most effectively raise and deal with sensitive issues, and so forth.

Goal-directed simulation of this kind is a cognitive process that may be supported by regions of both the default and the task-positive network, particularly regions of the task positive network involved in cognitive control. When we formulate a plan to solve a problem in the future, we need to keep in mind any information that might be relevant to the problem and its solution, make decisions as to how to proceed, and envision a sequence of actions that could lead to a solution. These types of cognitive processes have been researched in the context of executive

function and cognitive control (Badre & D'Esposito, 2009; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Norman & Shallice, 1980) and have been associated with activations in regions pertaining to the task-positive network, such as the lateral prefrontal cortex (Miller & Cohen, 2001; Koechlin, Ody, & Kouneiher, 2003; Rushworth, Hadland, Paus, & Sipila, 2002). In particular, the mid-DLPFC (Brodman area 9/46) appears to be critical for tasks that require encoding action sequences, coordinating actions in relation to internal goals, and maintaining abstract sequential movement plans (Badre & D'Esposito, 2009; Badre, Hoffman, Cooney, & D'Esposito, 2009), thus rendering it likely that DLPFC is engaged during problem-solving simulations. The aforementioned studies of executive function and cognitive control have typically examined executive demands associated with the manipulation and control of impersonal information, such as visuospatial patterns. Few studies, however, have examined problem-solving processes using real-world scenarios as task stimuli.

Given the diverse mental processes that are integral to problem-solving simulations, we expect their neural basis to be composed of regions from both the default and the task-positive network. However, such a hypothesis would be incongruent with the anticorrelation of the two networks. One recent study has provided evidence for the coactivation of areas of the default and the task-positive network (Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010). Spreng and colleagues revealed that while participants silently formulated plans for their personal future in order to attain goals, the default network was coactive with regions associated with cognitive control and executive function, including DLPFC.

To investigate whether the default network and executive regions can also be coactive in the context of goal-directed problem-solving simulations, we designed a problem-solving task based on an earlier cognitive paradigm (Patalano & Seifert, 1997), in which participants were

asked to imagine themselves (i.e., simulate) actively solving a problem. Participants were presented with imaginary scenarios, in which they needed to solve several specific problems and were given cues that could aid formulating a plan to solve each problem. We hypothesized that, relative to a semantic elaboration task, participants' problem-solving simulations would recruit core regions of the default network and executive regions. We predicted co-activation of PCC because of its central role in default mode processes (Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Buckner et al., 2009; Hagman et al., 2008) and of DLPFC because of its involvement in coordinating and maintaining action sequences and goals (Badre & D'Esposito, 2009; Botvinick et al., 2001; Norman & Shallice, 1980). Further, we expected activity of these default and executive regions to be coupled as a functional network during goal-directed simulation.

Material and methods

Participants

Twenty-nine healthy young adults (mean age = 22.4 years, *SD* = 3.1; 16 women) gave written consent and participated in the experiment in accordance with the guidelines set forth by the Committee on the Use of Human Subjects in Research at Harvard University and the Human Subjects Research Committee at Massachusetts General Hospital. All participants had normal or corrected-to-normal vision, reported no history of neurological or psychiatric conditions, and were right-handed native English speakers.

Materials and procedure

The simulation task was designed to present participants with problems to which they could easily relate and which they could imagine solving themselves in the future. To perform the simulation task, participants read and then kept in mind a scenario and an associated problem while imagining themselves in the setting specified in the scenario, solving the problem. We

based our task on a scenario from a cognitive paradigm (Patalano & Seifert, 1997) in which an individual is asked to imagine being left alone in a friend's dorm room, and to solve a number of problems that then arise. We expanded the number of scenarios in the original paradigm from one to six: being left alone in a friend's dormitory room, volunteering in a local retirement community, navigating a new neighborhood, organizing a camping trip, house-sitting for family-friends, and planning a class research project. We devised ten unique problems that an individual could encounter in each scenario. However, each participant was only presented with five of the ten problems that were associated with each scenario, whereby fourteen participants were randomly assigned one set of five problems, and the remaining fifteen participants simulated the other set of five problems.

In order to simulate solving the problems pertaining to each scenario, participants were given cues that could aid formulating a plan to solve each problem. One such scenario took place in a friend's dormitory room, where participants imagined being left alone. As one of the problems, participants imagined trying on the friend's class ring and being unable to remove it. Soap was suggested as a possible object that could help them solve the problem, and participants simulated removing the class ring using soap. Thus, subjects imagined both the problem solving process and the resulting solution to the problem. By providing participants with a word for an object (referred to as "object-word") that allowed them to solve each problem in a scenario, we sought increased experimental control over the specific content of their mental simulations.

As a comparison condition we used a semantic elaboration task for which participants silently generated semantically associated words. Since the future simulation task was not based on problems that participants actually faced in their everyday lives, there was a possibility that participants relied mostly on semantic rather than episodic forms of knowledge when imagining

themselves in the scenarios. To investigate whether goal-directed simulation in our paradigm is merely a form of semantic elaboration, the control task was designed to engage regions of the semantic network (Binder, Desay, Graves, & Conant, 2009). Participants were asked to silently generate words that were semantically associated with a cue word. Cue words were comprised of object-words and were counterbalanced across subjects.

Prior to scanning, participants became familiar with both experimental tasks by completing one trial of each condition on a laptop computer. In an event-related design in the scanner participants were presented with three runs that were self-paced except for fixed simulation, association, and rating periods. Each run consisted of ten trials of each condition (30 total per condition); the order of conditions was counterbalanced across participants. Within a run, subjects were presented with two blocks of five simulations trials that alternated with two blocks of five association trials. For the simulation task, participants read a short scenario and performed a button press to indicate when they had finished reading. They were then presented with the description of a problem that could occur in the context of the given scenario, and with the object-word that could be used to solve this problem. Participants pressed a button to advance to the subsequent screen, which instructed them to imagine themselves in the scenario faced with the problem and interacting with the object in order to solve the problem. This simulation period was fixed and lasted 7.5 seconds. Following the simulation period, participants rated the vividness of their simulation on a scale from one to four, with four being most vivid. For each simulation run, participants read two scenarios that were each followed by five associated problems. See Figure 2.1 for the sequence of stimuli participants saw in the scanner.

The first screen of the semantic association condition displayed the task instructions; analogous to the simulation task, participants advanced to the next screen by pressing a button.

Participants viewed the object-word and pressed a button once they were ready to commence the association generation period, which was fixed and lasted 7.5 seconds. They then had 2.5 seconds to rate on a scale of one to four the ease with which they were able to generate semantic associates for the object-word (four being the easiest). Within each run, participants performed two blocks of five association tasks.

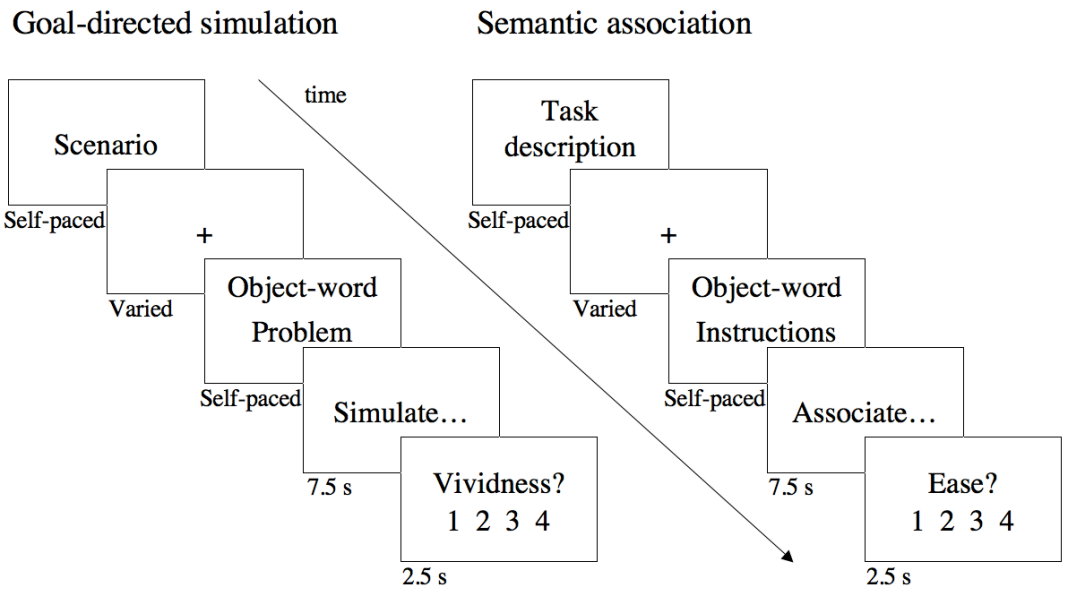

Figure 2.1. Task stimuli. Sequence of fMRI stimuli for each task condition.

All experimental trials were intermixed with varying periods of fixation trials, with fixation intervals ranging from one to four TRs ($M = 2.17$, $SD = 0.04$). The end of each run had six TRs of fixation. None of the object-words presented in the simulation and association task were repeated across tasks within participants, and object-words were randomized and counterbalanced across participants. All visual stimuli were presented in black on a white background using an Apple MacBook computer (Apple Computers) that ran PsyScope X B51 (Cohen, MacWhinney, Flatt, & Provost, 1993).

fMRI data collection

Participants were scanned using a 3-Tesla Tim Trio system (Siemens) with a 12-channel phased-array head coil. High-resolution three-dimensional T1-weighted images were acquired as anatomical scans [repetition time (TR), 2530 ms; echo time (TE), 3.44 ms; flip angle (FA), 7˚; 1.0 mm^3 isotropic voxels]. Functional data were collected using a gradient-echo echo-planar pulse sequence sensitive to blood oxygenation level-dependent (BOLD) contrast (TR, 2500 ms; TE, 30 ms; FA, 90˚; 3x3x3 mm^3 voxels; 36 axial slices parallel to plane of the anterior commissure-posterior commissure; 0.5 mm gap between slices). Head motion was restricted using a pillow and two padded clamps. Participants held a button box in their left hand, and earplugs were provided to attenuate scanner noise. Visual stimuli were projected onto a screen positioned at the head of the magnet bore, which was reflected in a mirror on top of the head coil.

fMRI data

Preprocessing

We used SPM8 (Wellcome Department of Cognitive Neurology, London, UK, www.fil.ion.ucl.ac.uk/spm) implemented in MATLAB (Mathworks, Sherborn, MA) to preprocess and analyze the fMRI data. We excluded the first four volumes of each run to avoid potential T1-equilibration effects and performed slice-timing corrections to the fifth slice. To remove systematic differences and movement-induced variance between sessions, images were realigned. Images were normalized to the Montreal Neurological Institute (MNI) EPI template (voxel size = 3 x 3 x 3 mm^3) and smoothed using a 6 mm full-width at half maximum (FWHM) Gaussian kernel. A high-pass filter with a cutoff value of 128 seconds was applied to the images to account for low-frequency drifts.

Task contrast analysis

For each participant we generated a general linear model (GLM) using SPM8 that was comprised of task effects, a mean and linear drift for each of the three functional runs, and six motion parameters. Task effects were modeled with the canonical hemodynamic response function, its temporal derivative, and its dispersion derivative (Friston et al., 1998) and included the following cognitive events: reading a scenario, reading an associated problem, reading instructions for the association task, as well as simulating and associating, which were each combined with their respective rating period. Simulation and association periods were combined with their rating periods to avoid regressing out relevant activation, as these periods always occurred subsequently without interspersed fixation. The resulting parameter estimates and *t*-contrast images of the conditions of interest at each voxel were then submitted to a second-level, random-effects analysis to create mean *t*-images. To identify neural activity associated with the goal-directed simulation distinct from semantic elaboration, we performed the direct whole-brain contrast with $p < .001$ uncorrected and a required cluster size of $k > 20$. We identified peak MNI coordinates of active regions based on the results of an automated peak-search algorithm. According to the same parameters, we also compared each condition of interest to fixation.

Specific regions of interest (ROIs) were generated by creating an 8 mm-radius sphere around peak coordinates that emerged from the whole-brain contrast. Parameter estimates for each ROI and condition were plotted to explore the underlying signal behind the whole-brain contrast results.

Task-related functional connectivity

In order to test the hypothesis that PCC and right and left DLPFC would behave as a functional network during simulation, we conducted a task-related functional connectivity

analysis using seed partial least squares (PLS; Burianova, McIntosh & Grady, 2010; McIntosh, 1999; McIntosh, Chau & Protzner, 2004). Seed PLS is a data-driven, multivariate functional connectivity analysis technique used to investigate the relationship between the activity of a set of seed regions and the activity in the rest of the brain. BOLD signal values from PCC (9, -50, 39; see Table 2.1), right DLPFC (33, 25, 45) and left DLPFC (-33, 31, 48), and their 26 neighborhood voxels were extracted and averaged from the third, fourth, and fifth TR post simulation trial onset. In order to assess the pattern of covariance between the three seed regions for the simulation condition, which indicates whether these regions are part of a functional network, the activity of the seeds was not averaged together. The activity of each seed was correlated with the activity in all other brain voxels across the five TRs, across participants. These correlations were then combined into a matrix and decomposed with singular value decomposition. This analysis resulted in a set of orthogonal latent variables which consists of A) a "singular value": the amount of covariance accounted for by the latent variable, B) a "singular profile": the pattern of covariance for the seed region with the rest of the brain (Figure 2.3), and C) a "singular image": the voxelwise pattern of brain regions that covary with the seed activity across the five-TR trial (Figure 2.4). The significance of the pattern of connectivity was determined by permutation testing, which randomly reorders the data matrix and calculates the singular values for a new set of latent variables for each reordering. Each newly computed singular value of a latent variable is then compared to the original latent variable, resulting in a probability of the permuted values that exceeds the original value. We conducted five hundred permutations.

In a second, independent step, the reliability of the associated brain voxel salience (or weight) from the singular image was determined by bootstrap resampling with replacement,

using 100 iterations, to estimate the standard errors for each voxel (Efron & Tibshirani, 1985). For each voxel, the salience/standard error ratio, or bootstrap ratio (BSR), was calculated. Peak voxels with a BSR greater than 3.23 were considered reliable and approximate a $p < .001$. Clusters containing at least 20 reliable voxels were extracted, and a local maximum for each cluster was defined as the voxel with a BSR higher than any other voxel in a 2 cm cube centered on that voxel. In seed PLS, the singular profile correlation values represent the relationship between activity in each seed region and the whole brain pattern identified in the analysis. If PCC were anticorrelated with DLPFC, the activity of these regions and their functional connectivity would be dissociated. However, if PCC and DLPFC behaved as a functional network of brain regions, their activity would covary together and be functionally connected with a distributed network of brain regions involved in goal-directed simulation. As summary measures of each subject's expression of each latent variable, we calculated "brain scores" by multiplying the BOLD signal in each voxel by each voxel's salience and summing across all brain voxels for each participant. We calculated the correlation between these brain scores and the seed values to assess the relation between the whole brain pattern and activity in the three seed regions. Based on the mean brain scores and the bootstrap, we calculated 95% confidence intervals, which can determine similarities and differences in correlation magnitude between the seed activity and the covarying brain activity, depending on whether or not the confidence intervals overlap.

Results

Behavioral findings

The behavioral ratings of vividness and ease, which we collected after each simulation and association period, confirmed that participants complied with the task. Participants were able to imagine solving problems with moderate vividness (mean vividness = 1.82, $SD = .39$) and did

not judge semantic associations to be too easy (mean ease = 1.77, *SD* = .29). Participants provided a rating for almost all trials (6.73% missing responses).

fMRI results

GLM results

The simulation task, relative to semantic association, engaged PCC, the right middle temporal gyrus, right MPFC, the right temporo-parietal junction, and the left inferior parietal lobule. These regions are consistent with the default network (Buckner et al., 2008; Fox et al., 2005; Raichle et al., 2001; Table 2.1; Figure 2.2A).

Table 2.1

Peak regions of activation for goal-directed simulation > semantic association

			MNI coordinates			
Lat	**Region**	**BA**	***x***	***y***	***z***	***t***
R	TPJ	39	48	-65	24	6.81
L	IPL	19	-36	-83	39	6.37
B	PCC	31	9	-50	39	5.73
R	DLPFC	9/46	33	25	45	5.53
R	MTG/ITS	21	48	-11	-21	5.50
B	PCu	7	-9	-56	63	5.45
L	DLPFC	9/46	-33	31	48	4.97
L	PCC	31	-9	-31	41	4.85
L	SMG	40	-57	-23	36	4.62
R	SMG	40	63	-23	30	4.43
L	PCG	3/4	-39	-32	54	4.41
R	ITG	37	48	-59	-9	4.11
R	MPFC	9	7	49	28	4.10
R	AMG		24	-2	-21	3.83

Note. Lat = Laterality, B = Bilateral, L = Left, R = Right, BA = Brodman's Area, AMG = Amygdala, IPL = Inferior parietal lobule, ITS = Inferior temporal sulcus, ITG = Inferior temporal gyrus, MTG = Middle temporal gyrus, PCu = Precuneus, SMG = Supramarginal gyrus, TPJ = Temporoparietal junction. Locations of the maxima are reported in the stereotaxic coordinates of MNI space.

Additional activity was observed during goal-directed simulation in bilateral DLPFC (Figure 2.2B), regions associated with cognitive control and working memory (Badre & D'Esposito, 2009; D'Esposito et al., 1995; Vincent et al., 2008). The ROI parameter estimates of PCC (9 -50 28), MPFC (7 49 28), and right (33 25 45) and left DLPFC (-33 31 48) illustrate that these regions were more strongly engaged or less deactivated during simulation than during association (Figure 2.2C).

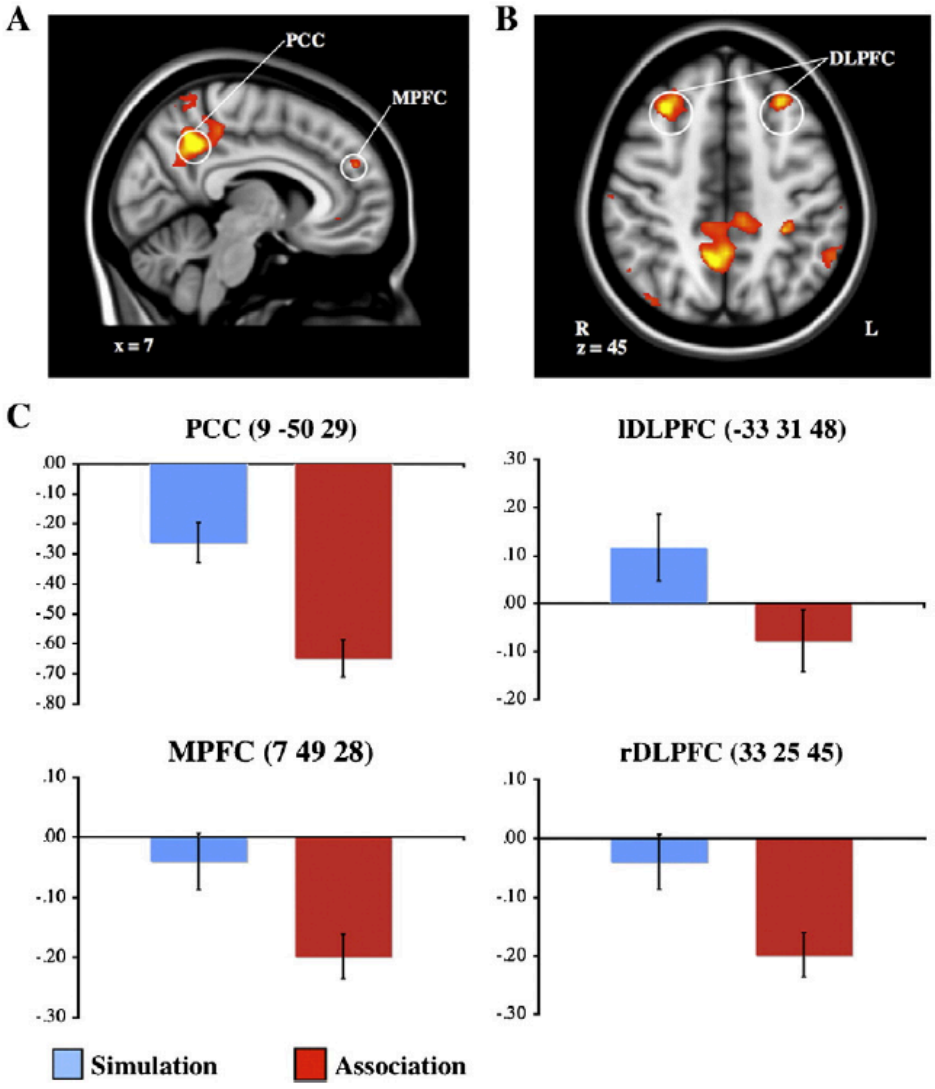

Figure 2.2. Goal-directed simulation > semantic association. Activations in regions of the default network and regions of executive function, including A. PCC and MPFC, and B. bilateral DLPFC. DLPFC, MPFC, and PCC parameter estimates for each condition are displayed in C. On the Y-axis is the mean parameter estimate, and error bars are standard error of the mean (SEM).

Relative to simulation, semantic association was associated with bilateral anterior insula, lingual gyrus, left medial superior frontal gyrus, and inferior frontal gyrus activity (Table 2.2).

Table 2.2

Peak regions of activation for semantic association > goal-directed simulation

			MNI coordinates			
Lat	**Region**	**BA**	***x***	***y***	***z***	***t***
L	aIfO		-33	19	0	7.24
B	MSFG	6	-6	16	51	7.21
L	IFG	9	-51	19	33	6.33
L	PreCG	4	-45	-8	60	4.98
R	LG	18	18	-89	-3	4.85
L	LG	18	-6	-86	-6	4.85
R	aIfO		33	25	0	4.36

Note. aIfO = Anterior insula/frontal operculum, IFG = Inferior frontal gyrus, LG = Lingual gyrus, MSFG = Medial superior frontal gyrus, PreCG = Precentral gyrus.

PCC, MPFC, and right and left DLPFC were deactivated during association relative to fixation (Figure 2.2C). Semantic network regions such as alfO and LG were more active during association compared to fixation (Supplemental Figure 2.2; Supplemental Table 2.2), whereas the contrast of simulation over fixation revealed activations in lDLPFC and frontal areas (Supplemental Figure 2.1; Supplemental Table 2.1).

Task-related functional connectivity

The seed PLS analysis revealed a significant pattern of task-related functional connectivity with one significant latent variable (p = .002, accounting for 62.72% of the covariance). During simulation, measures of overall brain activity were significantly correlated with activity in the three seed regions, across participants. All three seed regions reliably covaried together during simulation, See Figure 2.3.

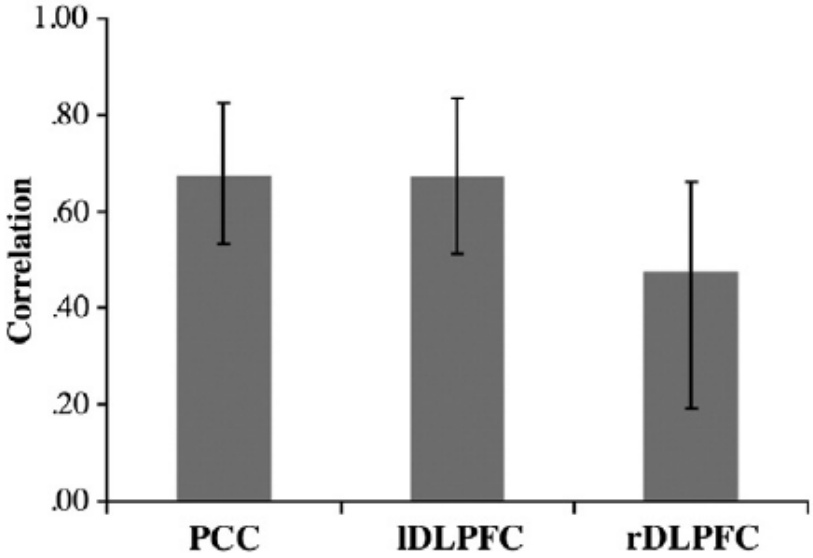

Figure 2.3. Correlations of activity in the PCC, lDLPFC, and rDLPFC seeds with their respective brain scores show how activity in the three seeds covaries with activity in the entire network. Error bars represent 95% confidence intervals based on the bootstrap, which indicate no differences in the pattern of connectivity between the three seed regions.

PCC and DLPFC seed regions were functionally associated with a distributed network of brain regions across the entire five-TR trial. This distributed functional network included MPFC, lateral parietal regions, lateral temporal regions, and superior frontal regions. The medial temporal lobes were also functionally recruited, but only in the first three timepoints of the trial. See Table 2.3 and Figure 2.4 for associated regions at each TR.

Table 2.3

Regions functionally connected with PCC and DLPFC during goal-directed simulation for each TR

		MNI coordinates			
Lat	**Region**	***x***	***y***	***z***	**BSR**
TR 2					
L	PCC	-12	-42	33	5.45
L	ITG	-48	-51	-21	8.58
R	PreCG	33	-27	54	8.22
R	IFG	54	24	15	7.59
L	Thal	-9	-18	9	7.41
L	MOG	-39	-81	6	7.23
R	CALG	21	-72	12	7.13
L	MSFG	-6	42	42	6.95
R	ATL	66	-9	-9	6.82
L	OP	-9	-99	3	6.76
R	PHG	27	-24	-27	6.59
B	MPFC	-6	54	15	6.46
L	PreCG	-63	-3	30	6.32
L	MTG	-48	-51	9	6.16
R	RSC	12	-48	6	5.91
L	IFG	-51	21	18	5.88
L	IPL	-48	-45	30	5.79
L	aIfO	-42	-15	9	5.37
L	MFG	-42	6	54	5.31
TR 3					
B	PCC	15	-48	39	8.77
R	DLPFC	30	24	42	6.98
L	DLPFC	-45	3	60	5.59
L	ATL	-45	15	-33	8.71
R	PHG	21	3	-21	8.69
R	MSFG	12	63	30	8.46
L	ITG	-48	-54	-21	7.91
R	ITG	51	-6	-33	7.72
R	PC	9	-81	-27	7.28
L	Thal	-18	-30	3	7.23
L	AG	-42	-63	42	7.13
L	OP	-30	-99	-12	6.89

Table 2.3 (continued)

L	Thal	-18	-30	3	7.23
L	AG	-42	-63	42	7.13
L	OP	-30	-99	-12	6.89
R	Thal	9	-9	6	6.88
L	PHG	-33	-18	-30	6.76
R	MTOG	51	-66	27	6.65
R	IPL	57	-39	57	6.45
L	IFG	-51	21	18	6.40
L	OP	-9	-105	-12	6.26
R	IFG	36	30	15	6.01
L	FP	-54	36	-9	5.98
R	PreCG	30	-18	60	5.95
L	CALG	-18	-60	6	5.84
L	MSFG	-12	39	45	5.62
L	VMPFC	-3	51	-9	5.47
L	STG	-45	-24	9	5.25
L	PC	-30	-75	-33	5.19
L	ITG	-54	-9	-36	5.01
L	Brainstem	-6	-30	-36	4.91
R	STG	63	-27	12	4.76
L	MPFC	-6	54	12	4.38
TR 4					
B	PCC/RSC	15	-45	42	9.62
R	DLPFC	30	24	42	8.54
L	DLPFC	-36	21	24	6.14
R	FP	39	36	-15	8.16
L	ITG	-48	-54	-21	7.95
B	VMPFC	-6	48	-9	7.89
R	STG	36	6	-18	7.13
R	ITG	48	-30	-24	6.88
R	IFG	36	30	15	6.53
R	AG	36	-66	45	5.95
R	PC	6	-81	-27	5.91
R	MSFG	12	60	30	5.89
L	Thal	-9	-9	9	5.82
R	SPL	21	-63	69	5.76
L	STG	-36	9	-36	5.34
R	SMG	48	-45	36	5.33
L	SPL	-33	-69	54	5.32
L	PCu	-3	-72	60	5.21

Table 2.3 (continued)

R	Brainstem	6	-39	-45	5.13
L	aIfO	-39	3	-12	5.07
R	MOG	48	-72	27	4.96
L	HC	-33	-24	-12	4.95
R	HC	33	-32	-12	5.56
TR 5					
R	PCC	15	-54	39	9.17
L	PCC	-17	-46	39	7.99
R	DLPFC	30	24	42	9.92
R	SPL	30	-57	72	8.11
R	PreCG	42	-3	24	7.60
L	IOG	-48	-72	-18	7.26
R	MSFG	12	63	27	6.47
L	VMPFC	-6	48	-12	6.39
R	PC	33	-72	-36	6.21
L	CT	-27	-78	-33	6.15
R	AG	39	-66	45	5.85
R	FP	48	36	-15	5.84
L	ITG	-45	-33	-18	5.82
R	aIfO	36	3	-15	5.31
R	IFG	33	27	18	5.28
L	PHG	-36	-12	-27	5.23
L	AG	-39	-69	42	4.82
R	SMG	60	-36	54	4.73
L	ATL	-51	9	-36	4.43
TR 6					
R	PCC	6	-45	36	9.60
L	PCC	-18	-48	36	7.99
R	DLPFC	30	21	42	9.90
L	DLPFC	-18	15	42	8.23
R	PC	30	-72	-27	8.63
R	PreCG	33	-30	54	7.96
R	AG	39	-69	39	7.53
R	MSFG	12	63	30	7.29
L	IOG	-48	-72	-15	7.27
R	SMG	48	-45	36	6.84
L	AG	-36	-69	42	6.58
R	IFG	36	30	18	6.16
R	SMA	6	3	48	6.03

Table 2.3 (continued)

L	PC	-30	-78	-33	6.02
R	aIfO	39	-3	0	5.17
L	MOG	-24	-81	12	5.08
R	SPL	27	-60	72	4.46

Note. AG = Angular gyrus, ATL = Anterior temporal lobe, CALG = Calcarine gyrus, CT = Cerebellar tonsil, FP = Frontal pole, HC = Hippocampus, IOG = Inferior occipital gyrus, LOG = Lateral orbital gyrus, MFG = Middle frontal gyrus, MOG = Middle occipital gyrus, MTOG = Middle temporo-occipital gyrus, OP = Occipital pole, PC = Pyramis of the cerebellum, PHG = Parahippocampal gyrus, RSC = Retrosplenial cortex, SMA = Supplementary motor area, STG = Superior temporal gyrus, STS = Superior temporal sulcus, Thal = Thalamus, VMPFC = Ventromedial prefrontal cortex.

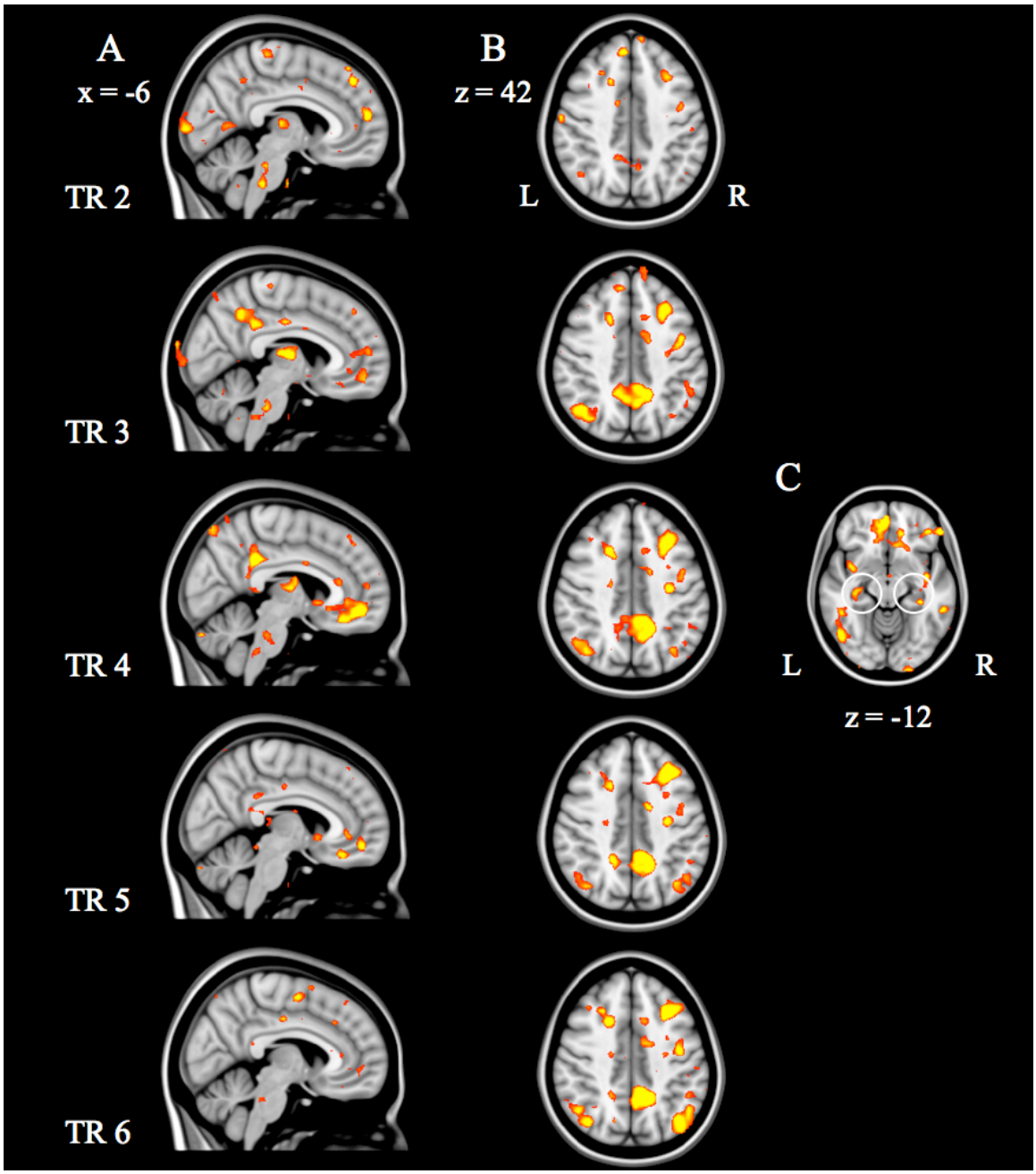

Figure 2.4. Regions of the distributed functional network in the seed PLS analysis, including A. PCC and MPFC, B. DLPFC and PCC, and C. HC development across TRs. Activity in PCC and DLPFC are coupled across all five TRs. This functional network included the additional recruitment of MPFC and parietal regions. Recruitment of the hippocampus was restricted to the fourth TR (circled in C).

Discussion

The present study investigated the neural correlates of simulations aimed at solving a set of problems in the future. This goal-directed task involves introspective, self-referential processing, and also requires formulating a plan to solve the problem, integrating and sustaining relevant information, and maintaining an abstract sequence of steps leading to the problem's solution. Relative to semantic association, problem-solving simulations were associated with activations in MPFC, PCC, the posterior temporoparietal junction, the inferior parietal lobule, and the middle temporal gyrus, all of which are regions that make up the default network (Buckner et al., 2008). This finding is in line with previous research on the function of the default network, showing that it is engaged during internally focused, self-referential mental projections (Buckner & Carroll, 2007). Problem-solving simulations also engaged executive regions, including bilateral DLPFC, which is part of the task-positive network (Badre & D'Esposito, 2009; Fox et al., 2005; Toro et al., 2008). Compared to semantic association, problem-solving simulations may have triggered more self-referential and spatial processing and required more working memory to keep in mind the scenarios and associated problems. Our seed PLS analysis confirmed that PCC and DLPFC can behave as a functional network: The seeds were functionally connected with a distributed network of regions that consisted of default network and executive regions, both of which appear to be involved in goal-directed simulation. This finding provides novel evidence of coupling between components of the default network and executive regions that have been associated with cognitive control during goal-directed mental simulation.

The seed regions selected for the task-related functional connectivity analysis have been previously identified as important components of their respective networks. PCC, which

remained more active throughout the goal-directed simulation task relative to semantic elaboration, connects all of the components of the default network (Hagman et al., 2008). Previous research has suggested that PCC plays an important role in spatial processing (Spreng et al., 2009; Vogt, Vogt, & Laureys, 2006), specifically in generating the context in which scenarios are situated (Szpunar et al., 2009), which represents a feature of the simulation task that clearly distinguishes it from semantic elaboration. Szpunar and colleagues (2009) have argued that PCC serves to reinstate familiar contextual settings from memory and is often coactive with parahippocampal cortex, which was found to covary with PCC in the functional connectivity analysis. When participants in the present experiment were directed to imagine a friend's dormitory room, a local retirement community, or a camping site, they may have used PCC and parahippocampal cortex to reconstruct familiar contexts for each setting from memory.

In addition to the recruitment of PCC, goal-directed simulations were associated with activations of bilateral DLPFC, which were also selected as seed regions. The engagement of DLPFC is most likely attributable to working memory and cognitive control demands of the simulation task, which we would expect to exceed those of the semantic association task. Regions of the prefrontal cortex have been found to support the coordination of actions and thoughts related to internal goals (Koechlin et al., 2003), and DLPFC in particular appears to play an important role in encoding action sequences, coordinating actions in relation to goals, and maintaining abstract sequential movement plans (Badre & D'Esposito, 2009; Badre et al., 2009). A recent study found that personal goals which were difficult to construct and varied in content, time-frame, emotional valence, and level of abstractness, engaged DLPFC, indicating that DLPFC involvement may be important for generalized goal-directed projection (Packer & Cunningham, 2009).

A series of previous experiments has associated MPFC with self-referential processing (D'Argembeau et al., 2007; Gutchess, Kensinger, Yoon, & Schacter, 2007; Gutchess, Kensinger, & Schacter, 2010; Macrae, Moran, Heatherton, Banfield, & Kelley, 2004), and it has been hypothesized to be important for assessing the self-relevance of any type of information or representation (Northoff et al., 2006; Schmitz & Johnson, 2007). MPFC appears to support diverse self-judgments, including judgments about one's personality traits, current mental states, and physical attributes, which are important to assess in order to decide which future actions to take (Jenkins & Mitchell, 2007; Seitz, Franz, & Anzari, 2009). Self-assessment and self-control of actions are critical components of problem-solving. Involvement of MPFC in such mental processes is only enhanced if participants imagine personal as opposed to nonpersonal future goals (D'Argembeau et al., 2010). In line with all of these previous findings, MPFC was likely engaged by the present paradigm when participants imagined themselves in each given situation, assessed the self-relevance of the provided scenarios, and possibly took into account their current mental state and personality traits while formulating a plan to solve each problem.

As part of the distributed functional network associated with PCC and DLPFC, medial temporal lobe regions were recruited early on during the simulation period. Our analysis showed bilateral hippocampus, which has been implicated in relational processing (e.g., Eichenbaum & Cohen, 2001) and, more specifically, the recombination and encoding of details from disparate past experiences into imagined future events (Schacter & Addis, 2007, 2009). Although the hippocampal system has most often been associated with the encoding or retrieval of memories, there is a growing body of work suggesting that it plays an important role in the ability to envision events in the future (e.g., Buckner, 2010). During the initial phase of the problem-solving simulation, the hippocampus was likely involved in constructing the simulation by

helping to piece together new representations based on past experiences (e.g., a time participants tried to get a ring off a finger, were under stress, used soap, etc.) in order to formulate a solution to the problem, and to "pre-experience" the event.

The coupling of PCC and DLPFC during the simulation task provides additional evidence concerning the relationship between default and executive regions. In most observations of the default network, activity decreases with increasing task-positive network activation (Kelly, Uddin, Biswal, Castellanos, & Milham, 2007) and task difficulty (McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003). There are very few studies that have reported regions of both networks to be active in parallel. Default network and executive system regions may contribute to insight during creative thinking (Kounios et al., 2006, 2008; Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009), mind wandering (Christoff et al., 2009), and autobiographical planning (Spreng et al., 2010). Spreng and colleagues showed that while participants formulated plans for their personal future, the default network (e.g., PCC, MPFC, hippocampus) was coactive with regions associated with cognitive control and executive function (e.g., DLPFC, anterior extent of the inferior parietal lobule). In another autobiographical planning task, however, planning personal and non-personal events was only supported by default network regions (D'Argembeau et al., 2010). Differences between the autobiographical planning tasks may account for the distinct findings, as participants in the latter experiment merely imagined future events that were relevant to personal goals, whereas Spreng et al.'s (2010) participants constructed strategic plans to reach desired goal states. Because similar strategic processes are required for problem-solving simulations, they may account for the recruitment of executive regions.

Simulating how to solve a problem in the future may be part of a group of cognitive processes that allow task-positive network regions to be coactive with default network regions. Problem-solving simulations and personal planning are both internally focused, self-referential, and directed toward a future goal. People engage in these mental processes frequently across the life span (D'Argembeau, 2011; Gollwitzer, 1999). Further studies will be needed to investigate the range of situations under which regions from both the default and task-positive networks can be engaged simultaneously and cooperatively. Future research will also be required to examine whether anticorrelations between default and task-positive network regions are task-dependent and whether they might differ between intrinsic and task-evoked activity. It is also yet to be determined whether methods of connectivity analysis could influence findings of anticorrelations in task-evoked analyses. Clarification of such conceptual and methodological issues should provide a stronger basis than currently exists for developing a cognitive neuroscience account of how mental simulation contributes to solving future problems.

Paper 2:

Gerlach, K. D., Spreng, R. N., Madore, K. P., & Schacter, D. L. (under review). Future planning: Default network activity couples with frontoparietal control network and reward-processing regions during process and outcome simulations.

Abstract

We spend much of our daily lives planning for goals we want to achieve and imagining what will happen when we attain them. Despite the prevalence of such goal-directed future simulations, the majority of neuroimaging studies on planning have focused on executive processes in the frontal lobe; little is known about the ability to imagine a series of steps leading up to a goal or to pre-experience achieving a goal. This experiment examined the neural basis of *process simulations*, during which participants imagined themselves going through steps toward attaining a goal, and *outcome simulations*, during which participants imagined events they associated with achieving a goal. In the scanner, participants engaged in these simulation tasks and a control task of odd/even judgments. Based on previous findings from related goal-directed simulations, we hypothesized that participants' process simulations would recruit regions of the default and frontoparietal control network. We predicted that outcome simulations, which allow us to anticipate the affective consequences of achieving a goal, would recruit default and reward-processing regions. Our analysis of brain activity that covaried with process and outcome simulations confirmed these hypotheses. A functional connectivity analysis with posterior cingulate, dorsolateral prefrontal cortex, and anterior inferior parietal lobule seeds showed that activity in these regions was correlated during process simulations and associated with a distributed network of other default and frontoparietal control network regions. During outcome simulations, medial prefrontal cortex and amygdala seeds covaried together and formed a functional network with other default and reward-processing regions.

Future planning: Default network activity couples with frontoparietal control network and reward-processing regions during process and outcome simulations.

Episodic future simulation, our ability to construct and imagine a hypothetical personal event or series of events in the future (Schacter et al., 2008; Taylor & Schneider, 1989), has been at the center of much recent behavioral and functional neuroimaging (fMRI) research (e.g., Buckner & Carroll, 2007; Gilbert & Wilson, 2007; Schacter et al., 2007; Szpunar, 2010; for a recent review, see Schacter et al., 2012). In everyday life, people frequently engage in episodic future simulation (D'Argembeau et al., 2011; Klinger & Cox, 1987) and tend to plan and anticipate personal goals when they do so (Baird, Smallwood, & Schooler, 2011; D'Argembeau & Mathy, 2011). Two types of such goal-directed simulations will be the focus of this paper: 1) Imagining attaining a desired goal, and 2) constructing a detailed plan of how to reach a certain goal (Oettingen & Gollwitzer, 2010; Taylor & Pham, 1996). A large body of research has examined different aspects of planning, including diverse planning tasks (Garden, Phillips, & McPherson, 2001; Hayes-Roth & Hayes-Roth, 1979; Shallice, 1982), theoretical models of planning (e.g., Ajzen, 1991; Miller et al., 1960), and planning deficits due to neurological damage (e.g., Morris & Ward, 2005; Penfield & Evans, 1935). By contrast, episodic future simulations, specifically in the context of personal goals and plans, have received comparatively little attention (for discussion, see Schacter, 2012).

A few behavioral studies on personal goal achievement have investigated the effects of episodic future simulations (e.g., Chan & Cameron, 2012; Papies, Aarts, & de Vries, 2009; Spreng & Levine, in press; Taylor et al., 1998). In a series of experiments measuring undergraduates' performance on midterm exams and a class project, Taylor and Pham (Pham & Taylor, 1999; Taylor & Pham, 1996, 1999) found that *process simulations*, during which

students imagined the steps they should take in order to obtain a good grade or complete a project (imagining where and when they would study, what measures they would have to take in order to progress in their studying) proved more beneficial than *outcome simulations*, during which students envisioned themselves having achieved the goal of a good grade (being handed their exam with an A grade, feeling happy). Compared to students in the outcome simulation condition, participants in the process simulation condition started studying earlier, spent more hours studying, performed better on exams, were less anxious, and suffered from the planning fallacy to a smaller extent. In a related line of research on *implementation intentions*, where participants form an association between a cue and the desired behavior ("If I encounter X, then I will perform Y"; Gollwitzer, 1999; Gollwitzer & Sheeran, 2006), implementation intentions that were accompanied by mental simulations of the future behavior rendered the goal behavior more likely to be carried out (Gollwitzer & Brandstätter, 1997; Papies et al., 2009). For example, participants who had formed implementation intentions to write a report on how they spent Christmas Eve by specifying and visualizing when and where they would start to write the report were more likely to complete the assignment earlier and within the specified time window than participants who had only formed goal intentions (Gollwitzer & Brandstätter, 1997).

Unlike episodic simulations of the steps to be taken toward a goal, simulations of desired future outcomes allow us to pre-experience the events' affective impact and reward value (Boyer, 2008). This characteristic of outcome simulations has been shown to attenuate temporal discounting, the tendency to devalue delayed relative to immediate rewards (Benoit et al., 2011; Peters & Büchel, 2010a). In the paradigms used by Benoit et al. (2011) and Peters and Büchel (2010a), participants were presented with immediate and delayed rewards and engaged in episodic simulations of future events that they could experience if they received the reward. This

episodic simulation condition was compared to either wait time (Peters & Büchel, 2010a) or a semantic estimation of what the reward could purchase (Benoit et al., 2011). If participants imagined events they associated with receiving a reward, they tended to overcome any temporal discounting bias, that is, they expressed more willingness to wait for a delayed but larger reward. Imagining personal future events has also been linked to the eventual enactment of these events (Spreng & Levine, 2006; Spreng & Levin, in press; Weiler, Suchan, & Daum, 2010). Even though participants were not specifically instructed to imagine future personal goals, Spreng and Levine (in press) found that 59-64% of the imagined personal future events, which were supposed to be probable and specific in time and place, had actually occurred a year after participants simulated those events.

So far, no fMRI study has examined and compared the neural underpinnings of episodic simulations of the steps leading up to a personal goal and the events associated with achieving the desired goal. However, neuroimaging studies of episodic future simulations have consistently shown activations in the default network, a set of interconnected brain regions consisting of medial prefrontal cortex (mPFC), posterior cingulate cortex (pCC), medial and lateral temporal regions, and posterior inferior parietal lobule (pIPL; e.g., Buckner et al., 2008; D'Argembeau et al., 2010; Gusnard & Raichle, 2001; Yeo et al., 2011). In two recent fMRI studies on episodic simulations that were directed toward a specific goal, default network regions were shown to form functional networks with task-relevant regions outside of the default network (Gerlach, Spreng, Gilmore, & Schacter, 2011; Spreng et al., 2010). In one such study, Gerlach et al. (2011) required participants to simulate the process of solving a problem using a certain object (e.g., getting a friend's ring off your finger using soap) and revealed that default network regions and executive dorsolateral prefrontal cortex (dlPFC) were functionally coupled during the simulation.

Spreng and colleagues (2010) provided participants with the steps necessary to complete different life goals and asked them to sequence these goals into a coherent imaginative plan that could lead to the achievement of the goals. During this planning task, activity in the default network was coupled with the entire frontoparietal control network, consisting of rostrolateral prefrontal cortex (rlPFC), middle frontal gyrus (MFG), anterior insula/frontal operculum (aIfO), dorsal anterior cingulate cortex (daCC), precuneus (PCu), and anterior inferior parietal lobule (aIPL; Vincent et al., 2008; see also Spreng & Schacter, 2012, and Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013 for replication and extension).

Neuropsychological and neuroimaging studies of classic planning paradigms, such as the Tower of Hanoi or the Multiple Errands Task, have also consistently implicated prefrontal cortex regions, though none of these tasks involved episodic simulation of personal goals (e.g., Eslinger & Damasio, 1985; Goldstein, Bernard, Fenwik, Burgess, & McNeil, 1993; Luria, 1966; Morris & Ward, 2005). DlPFC activity has been repeatedly associated with improved performance on executive planning tasks such as the Tower of London (e.g., Baker et al., 1996; Dagher, Owen, Boecker, & Brooks, 1999; Rowe, Owen, Johnsrude, & Passingham, 2001), as well as more realistic multitasking procedures (e.g., Burgess, Veitch, de Lacy, Costello, & Shallice, 2000), suggesting that it plays a role in coordinating and maintaining behavior sequences and goals (Badre & D'Esposito, 2009; Botvinick 2008; Norman & Shallice, 1980).

Findings from patients with ventromedial prefrontal cortex (vmPFC) lesions have indicated that these patients are insensitive to future consequences and are often unable to decide on which steps to take toward a goal (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Tranel, & Damasio, 2000; Eslinger & Damasio, 1985). VmPFC, which is also a default network region that has been tied to self-referential processing (e.g., Amadio & Frith, 2006;

D'Argembeau et al., 2010; Gusnard, et al., 2001; Jenkins & Mitchell, 2007), should thus play a role in the ability to simulate future outcomes. A more rostral region of mPFC has also been implicated in the ability to pre-experience outcomes, particularly if they are associated with positive valence or rewards (Benoit et al, 2011; D'Argembeau et al., 2008; Sharot, Riccardi, Raio, & Phelps, 2007). In addition to mPFC, the experience of emotional valence and reward has been linked to a system of interconnected brain regions involved in affective and reward processing, including nucleus accumbens (NAcc), amygdala, insula, anterior cingulate cortex (aCC), and thalamus (e.g., Liu et al., 2011; Peters & Büchel, 2010b).

In the present fMRI study of realistic episodic simulations about personal goals, we examined patterns of brain activation for process simulations, during which participants imagined themselves going through a number of idiosyncratic steps toward achieving a goal, and outcome simulations, during which participants imagined a number of personal events they associated with achieving a goal. Based on studies of similar goal-directed simulations and executive planning (Baker et al., 1996; Gerlach, et al., 2011; Spreng et al, 2010), we hypothesized that participants' process simulations would recruit regions of the default and frontoparietal control networks. We expected activity in core nodes of these networks, such as pCC in the default network (Buckner et al., 2009; Fransson & Marrelec, 2008; Hagman et al., 2008), and aIPL and dlPFC in the frontoparietal control network (Spreng et al., 2013; Vincent et al., 2008) to be coupled as a functional network during process simulations.

Since outcome simulations allow participants to pre-experience the affective impact and reward value of achieving a goal, we hypothesized that they would be associated with regions that have been linked to emotion processing, such as the amygdala (e.g., Bechara, Damasio, & Damasio, 2003; Bechara, Damasio, Damasio, & Lee, 1999), and reward processing, such as the

NAcc and aCC (e.g., Peters, J., & Büchel, 2010ab; Liu et al., 2011). Given the prospective, self-referential nature of outcome simulations, we also expected default network regions, in particular medial prefrontal cortex based on its aforementioned role in the simulation of consequences and reward value (Benoit et al, 2011; D'Argembeau et al., 2008; Eslinger & Damasio, 1985), to be coupled with reward processing regions.

Methods

Participants

Twenty-eight healthy, right-handed young adults (mean age = 21.2 years, SD = 2.8; range = 18-28 years; 20 women) with normal or corrected-to-normal vision and no history of psychiatric or neurological conditions provided written consent and participated in the experiment in accordance with the guidelines of the Committee on the Use of Human Subjects in Research at Harvard University. All participants were native English speakers and were recruited from Harvard University and Boston University. Data from an additional three participants was discarded due to excessive movement in the scanner (one participant) and non-compliance with the task reflected in post-scan interviews (two participants).

Materials

The stimulus set consisted of 102 goals based on a large sample of personal goals we collected from an independent group of 21 young adults that were matched to our scanned group in terms of age ($t(47) = 1.56$, $p = .125$), gender ($\chi^2(1) = 2.10$, $p = .15$), and education ($t(47) = 1.06$, $p = .293$; see Supplementary Table 3.1 for the list of goals). This independent group was asked to generate at least 150 realistic personal goals that were attainable within the next five years and comprised neither habitual activities nor significant milestones such as graduating from college or getting married. For each goal participants indicated four sequential steps they

would take to reach the goal and four events or activities they associated with having accomplished the goal. For instance, for the goal of going on vacation, many participants imagined going online to compare prices for different destinations, booking a trip, packing a suitcase, and getting on a plane. Swimming in a pool, having a meal of local specialties, going snorkeling, and sleeping in were activities many participants associated with having achieved the goal of going on vacation. Participants also provided a rating of each goal's desirability on a scale of 1-100 (100 being most desirable).

We determined 102 goals with the necessary number of steps and associations to be similarly desirable and reliable across the sample. Common goals ranged from self-improvement (e.g., eating healthier food, improving your wardrobe) to new skill acquisition (e.g., learning to drive stick shift, learning how to paint), to activities with friends and family (e.g., going on family vacation, being in a friend's wedding). All goals were adapted to be 3-6 words long and to apply to both process and outcome simulations. Six goals were used for practice trials and 96 for fMRI scanning.

Design and Procedure

Prior to scanning, participants became familiar with all in-scanner tasks by completing 6 practice trials. The practice trials included 3 trials for the process simulation, for which they imagined 2, 3, and 4 steps necessary to achieve a goal, and 3 trials for the outcome simulation condition, for which they imagined 2, 3 and 4 plausible events associated with achieving the goal. We asked participants to produce a specific number of steps or events for each simulation in order to make the two conditions as equivalent as possible. This procedure also allowed us to test whether the number of imagined steps or events affected neural activity for each type of simulation. Following the practice trials, participants were asked to recount the content of their

simulations to ensure task compliance. In order to elicit realistic, idiosyncratic process and outcome simulations, we did not to prescribe the specific steps or events participants imagined.

In the scanner participants were presented with 8 experimental runs of 12 goal simulation trials. Goals were randomized and counterbalanced across conditions, number of steps/events, and participants, so that each run contained 6 outcome and 6 process simulations without repetitions across conditions. All experimental trials were intermixed with varying periods of an odd/even task ranging from 5 to 10 s in duration (Stark & Squire, 2001): Participants saw a number from 1 to 9 in the center of the screen and indicated through a button press whether it was odd or even; they had 2.5 s to do so for each number. Fixation, which typically elicits default network activity (Stark & Squire, 2001), was not used as a direct comparison task for process and outcome simulations, as we expected default network regions to also be engaged in process and outcome simulations.

For process simulation trials, participants were instructed to imagine themselves going through a set number of steps (2, 3, or 4) that would help them achieve a given goal. In outcome simulation trials, participants simulated a set number of events that they associated with having achieved a given goal. Both the instructions and the goal itself remained on screen for the duration of all trials. Trial duration was self-paced with a maximum duration of 30 seconds. Next, participants had 2.5 seconds to provide a success rating indicating whether they were able to generate a simulation and adhere to the task instructions. Runs were approximately 8 min long, and visual stimuli were presented in black, blue (process goals), or green (outcome goals) on a white background using a Lenovo Thinkpad laptop that runs EPrime.

Following the scan, participants received a randomized list of all the goals and were asked to provide a brief written description of each step/event imagined, which served as a

manipulation and task compliance check. Participants also provided behavioral ratings for each trial: On a scale of 1 – 7, they rated how detailed and difficult to generate each simulation had been (1 = *least detailed/difficult,* 7 = *most detailed/difficult*) and also indicated with a *yes* or *no* whether a given goal was one they wanted to pursue in real life. Participants also provided ratings on a 1 – 7 scale for how important and desirable the goal was, how confident they were that they would complete the goal, how motivated they were to achieve it, and how difficult they thought it would be to achieve the goal. It took participants 1.5 to 2 hours to complete this post-scan interview. The written descriptions of each imagined step or event allowed us to verify participants' adherence to the experimental manipulation. Any written description that was incomplete or did not comply with task instructions in the post-scan interview or that was rated unsuccessful in the scanner was excluded from behavioral and fMRI analyses.

fMRI data collection

We acquired high-resolution three-dimensional T1-weighted anatomical images [repetition time (TR), 2530 ms; echo time echo time (TE), 3.44 ms; flip angle (FA), 7°; 1.0 mm^3 isotropic voxels] as well as all functional images using a 3-T Tim Trio scanner (Siemens) with a 12-channel phased-array head coil. We collected the data for each participant's 8 experimental runs using a gradient-echo echo-planar pulse sequence sensitive to blood oxygenation level-dependent (BOLD) contrast (TR, 2500 ms; TE, 30 ms; FA, 90°; 2x2x2 mm^3 voxels; 39 axial slices parallel to the plane of the anterior commissure-posterior commissure; 0.5 mm gap between slices). Participants' head motion was minimized with a pillow and two padded clamps. They wore earplugs to decrease scanner noise and held a button box in their right hand. All visual stimuli were projected onto a screen at the head of the magnet bore, which participants viewed through a reflection in a mirror on top of the head coil.

fMRI data

Preprocessing

We used SPM2 (Wellcome Department of Cognitive Neurology, London, UK, www.fil.ion.ucl.ac.uk/spm) to preprocess all fMRI data. After excluding the first four volumes of each run to avoid T1-equilibration effects, we corrected the data for slice-dependent time shifts and for head motion within and across runs using a rigid body correction. Images were normalized to the standard space of the Montreal Neurological Institute (MNI) atlas and smoothed with a 6-mm full-width-at-half-maximum (FWHM) Gaussian kernel resulting in a voxel size of $2mm^3$.

Partial least squares

In order to analyze task-related brain activation, we performed a multivariate Partial Least Squares analysis (PLS; Krishnan-Williams, McIntosh, & Abdi, 2011; McIntosh, Bookstein, Haxby, & Grady, 1996; McIntosh et al., 2004). PLS identifies whole-brain activity patterns related to experimental tasks and is sensitive to distributed voxel response. It calculates a set of orthogonal components (Latent Variables, LVs) that best explain the covariance of distributed voxels across the whole brain with the experimental tasks. In contrast to univariate analyses, PLS thus does not examine the activity of any single voxel independently but instead identifies patterns of activity that covary with task conditions. In addition, it extracts these whole-brain activity patterns in one step, which renders correcting for multiple statistical comparisons unnecessary. Permutation tests determine the statistical significance of the LV as a whole, and bootstrap resampling with replacement determines the reliability of the effects.

The whole-brain data were analyzed as blocks of variable duration set to participants' self-paced simulation intervals. In the first PLS analysis, we reported on simulation and outcome

conditions, collapsing across the different numbers of imagined steps or events. PLS calculated a set of LVs based on the covariance matrix of the mean BOLD signal for each block and the experimental tasks: Process simulations, outcome simulations, and odd/even judgments. This calculation, which involved singular value decomposition of the matrix, resulted in a singular value for each orthogonal LV. The first LV always has the largest singular value, i.e., it explains the largest proportion of the covariance between the BOLD signal and the experimental conditions. The statistical significance of each LV was calculated using a permutation test with 500 permutations. The correlation matrix was thereby randomly reordered 500 times, and each time the singular values for a new set of latent variables were calculated. By comparing each resulting singular value of a latent variable to the original singular value, PLS establishes the probability of the permuted singular values that exceed the original value.

Each brain voxel was assigned a weight, or "salience", that reflects the covariance of its activity with the task on each LV. The sum of the product of each voxel's by each voxel's BOLD signal resulted in a so-called brain score for each participant, task, and LV. Brain scores indicate to what extent each participant expresses the LV's brain pattern. We calculated 100 bootstrap samples with replacement to determine whether the saliences for the brain voxels across participants for each LV were reliable based on the voxels' standard error (Davidson & MacKinnon, 2000; Efron & Tibshirani, 1985). We considered voxels with a bootstrap ratio (BSR; salience/standard error) > 2.58, $p < .01$, to be reliable. Local maxima, which we reported as MNI coordinates, were defined as voxels with the highest BSR within 2 cm^3 around them, consisted of clusters of more than 20 reliably activated voxels, and were more than 10 voxels apart from the next voxel peak. We calculated 95% confidence intervals for each BSR and

determined two conditions to be reliably different from each other if their confidence intervals did not overlap.

In a second block PLS analysis, we divided the process and outcome simulation trials into trials with 2, 3, and 4 steps/events. This also allowed us to test whether the number of imagined steps or events affected neural activity for each type of simulation.

Task-related functional connectivity

We hypothesized that during process simulation, default and frontoparietal control network regions would be functionally coupled. During outcome simulations, we expected default and reward processing regions to form a functional network. In order to test these hypotheses, we conducted a task-related functional connectivity analysis using "seed" PLS (Krishnan et al., 2011; McIntosh, 1999). Seed PLS examines the relationship between the activity of a set of seed regions and the activity in the rest of the brain. Across participants, the mean BOLD signal values of each group of seeds were correlated with the activity in all other brain voxels and combined into a matrix. Singular value decomposition of this matrix resulted in a set of orthogonal LVs. Each LV had a pattern of covariance for each seed region with the rest of the brain (singular profile; Figures 5 and 7) and a pattern of brain regions that covaried reliably with the seed activity (singular image; Figures 6 and 8). The significance and reliability of the pattern of connectivity of the distributed functional network was determined using permutation tests and bootstrap resampling as described above.

For process simulations, we extracted mean BOLD signal values from pCC (-10 -34 30), left aIPL (-46 -48 42), right aIPL (46 -50 46), left dlPFC (-34 32 45), and right dlPFC (40 44 26) along with their 26 neighborhood voxels. We also extracted mean BOLD signal values from mPFC (-10 58 28), left amygdala (-20 -6 -14), and right amygdala (16 -2 -20) for the outcome

simulation condition. For this seed PLS analysis, we required a BSR of 3.29 for peaks, which approximates a $p < .001$.

Results

Behavioral findings

Participants rated 95% (*SD* = 4%) of simulation trials in the scanner as successful and correctly identified 90% (*SD* = 5%) of all odd/even trials, confirming their ability to successfully perform all experimental tasks. According to the exclusion criteria described above, we were able to use 90% (*SD* = 7%) of goal trials for behavioral and fMRI analyses. Simulation periods increased significantly in duration according to the number of steps and events participants were instructed to imagine ($F(2, 54) = 109.44$, $p < .001$, $\eta_p^2 = .80$), providing evidence of participants' task compliance, and did not differ significantly between conditions ($F(1, 27) = 3.54$, $p = .07$, $\eta_p^2 = .12$). On average, it took participants 18 s (*SD* = 4) to simulate 2 steps/events, 21 seconds (*SD* = 5) to simulate 3 steps/events, and 24 s (*SD* = 4) to imagine 4 steps/events associated with a given goal.

Post-scan ratings. Participants were able to generate detailed goal simulations (*M* = 4.58 out of 7 for all scalar ratings, *SD* = 0.64) and remembered their outcome simulations to be slightly more detailed than their process simulations (see Table 3.1 for descriptive statistics per condition and paired *t*-tests). Participants found it relatively easy to think of steps or events for each goal in the scanner (*M* = 2.87, *SD* = 0.82) or to achieve the given goals in real life (*M* = 3.55, *SD* = 0.81). On average, participants shared 59% (*SD* = 14%) of the presented goals and categorized a slightly higher percentage of the goals for which they had undergone outcome simulations as personal goals. Based on the relatively low novelty ratings (*M* = 3.09, *SD* = 0.88), participants had apparently given many of the given goals prior consideration. They were quite

confident that they would be able to achieve the presented goals (M = 4.23, SD = 0.70) and were motivated to do so (M = 3.75, SD = 0.64). Goals in the outcome simulation condition were evaluated to be somewhat more important and desirable than goals in the process simulation condition; across conditions participants found the presented goals to be quite desirable (M = 4.27, SD = 0.71) and important (M = 3.65, SD = 0.73). These results show that participants' process and outcome simulations were relatively equivalent and confirm that the provided goals were relatable as well as relevant.

Table 3.1

Post-scan interview characteristics

	Process	Outcome	Paired *t*-tests	
	M (*SD*)	*M* (*SD*)	*t*	*p*-value
Detail	4.45 (0.67)	4.7 (0.73)	2.44	.02
Generation	2.82 (0.85)	2.94 (0.91)	1.04	.31
Goal	0.56 (0.17)	0.62 (0.16)	3.07	.005
Importance	3.50 (0.72)	3.74 (0.69)	3.94	.001
Desirability	4.03 (1.00)	4.38 (0.74)	2.39	.02
Novelty	3.09 (0.91)	3.10 (0.91)	0.12	.91
Confidence	4.26 (0.82)	4.23 (0.65)	-0.26	.80
Motivation	3.81 (0.95)	3.82 (0.63)	0.07	.95
Achievement	3.79 (1.37)	3.53 (0.82)	-1.44	.16

*Note***.** Behavioral ratings on a scale of 1-7 of each goal simulation (1 = *least,* 7 = *most*). "Generation" refers to how difficult it was to generate steps or events; "achievement" refers to how difficult it would be to achieve the goal in real life. "Goal" was coded as a binary variable (1 = *personal goal*, 0 = *not a personal goal*). All paired *t*-tests had 27 degrees of freedom and were two-tailed.

fMRI results

Partial least squares

The primary block PLS analysis resulted in two significant LVs. The first LV dissociated the two simulation tasks from the odd/even control task (p < .001; Figure 3.1). Both goal

simulation tasks were associated with increased activity in default network regions relative to the odd/even task (see Table 3.2 and Figure 3.2). This robust default network activity encompassed all of the main default network nodes, including posterior parietal and retrosplenial cortex, ventromedial prefrontal cortex, posterior parietal lobule, inferior frontal gyrus, as well as anterior and medial temporal lobes (Buckner et al., 2008; Gusnard & Raichle, 2001; see Supplementary Table 3.2 for odd/even > goal simulation peaks).

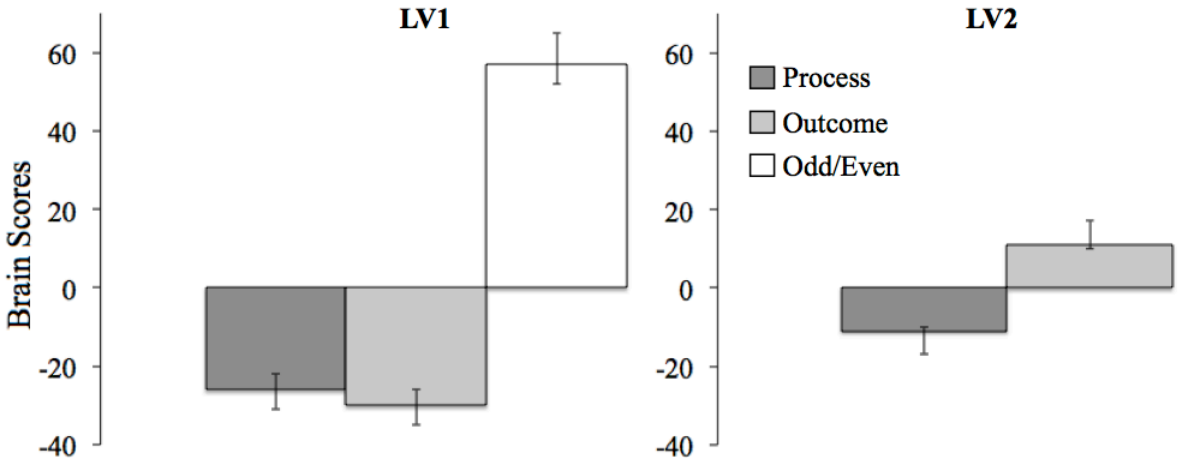

Figure 3.1. Block PLS analysis mean brain scores per condition. Data are shown for the PLS analysis that included the control condition (LV1) and the analysis that focused on the experimental conditions (LV2). Error bars represent the 95% bootstrapped confidence intervals.

Table 3.2

Peak regions of activation for Goal simulation > Odd/Even judgments

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
Goal simulation > Odd/Even judgments						
R	PHG	35/28	24	-34	-18	11.62
L	IFG	47/11	-40	28	-14	10.99
L	msPFC	6	-14	12	58	10.87
L	AG	39	-44	-72	32	10.04
L	IFG	45	-50	26	14	9.85
R	CT		42	-62	-42	9.76
R	PostCG	3	26	-30	62	7.48
L	Caud		-12	10	14	6.08
L	UC		-8	-88	-38	5.40
R	MTG	39	48	-60	24	5.07
R	MFG	6	30	12	48	4.96
R	IFG	11	36	38	-16	4.40
R	PCu	7	14	-58	60	3.99
R	mPFC	9	10	56	32	3.85

Note. Lat = Laterality, B = Bilateral, L = Left, R = Right, BA = Brodmann's Area, AG = Angular gyrus, Caud = Caudate, CT = Cerebellar tonsil, IFG = Inferior frontal gyrus, MFG = Middle frontal gyrus, msPFC = Medial superior prefrontal cortex, MTG = Middle temporal gyrus, PHG = Parahippocampal gyrus, PostCG = Postcentral gyrus, UC = Uvula of the cerebellum. Locations of the maxima are reported in the stereotaxic coordinates of MNI space.

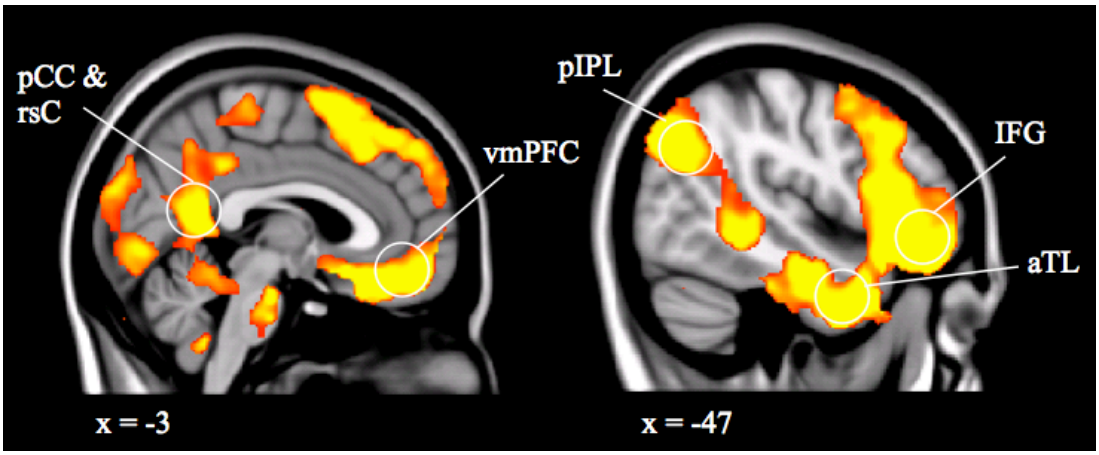

Figure 3.2. Goal simulations > Odd/Even judgments. Activations in regions of the default network, including posterior cingulate cortex, retrosplenial cortex (rsC), ventromedial prefrontal cortex, posterior inferior parietal lobule, inferior frontal gyrus, and anterior temporal lobe (aTL).

Since the first LV accounted for most of the covariance in the data (95.63%), we conducted a second PLS analysis with only the two experimental conditions in order to specifically target differences between process and outcome simulations (see also, St.-Laurent, Abdi, Burianova, & Grady, 2011). This analysis resulted in a significant pattern of activity that accounted for 100 % of the covariance in the data (p = .02; Figure 3.1) and identified brain regions where BOLD signal differed between process and outcome simulations. Regions that showed increased activity during process simulations compared to outcome simulations pertained to both the frontoparietal control and the default network (see Table 3.3 and Figure 3.3): Bilateral anterior inferior parietal lobule, anterior insula, dorsolateral prefrontal cortex, precuneus, and middle frontal gyrus make up the frontoparietal control network (Niendam et al., 2012; Vincent et al., 2008; Spreng et al., 2010), whereas posterior cingulate cortex, retrosplenial cortex, superior frontal gyrus, and the inferior frontal gyrus are part of the default network (Buckner et al., 2008; Spreng et al., 2013).

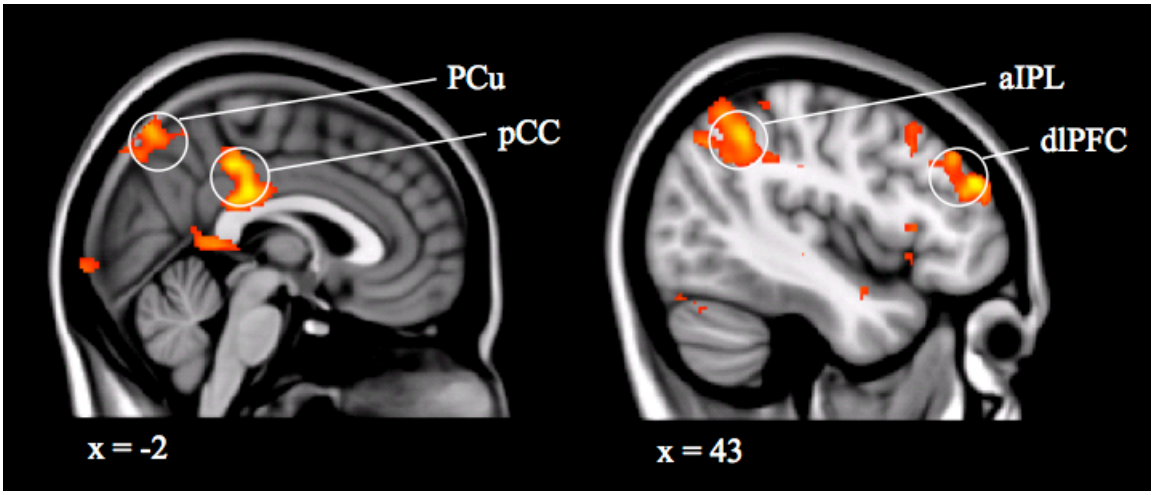

Figure 3.3. Process simulation > Outcome simulation. Activations in regions of the default network, including posterior cingulate cortex, and regions of the frontoparietal network, such as precuneus, anterior inferior parietal lobule, and dorsolateral prefrontal cortex.

Table 3.3

Peak regions of activation for Process simulation > Outcome simulation

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
Process simulation > Outcome simulation						
R	dlPFC	9	40	44	26	6.79
L	aIPL	40 / 7	-46	-48	42	5.89
R	aIPL	40 / 7	46	-50	46	5.71
B	pCC	23 / 31	-10	-34	30	5.69
L	islC		-16	-78	-44	5.61
R	MFG	32 / 8	6	30	34	5.23
R	PHG		34	-34	8	4.80
R	MFG	6	12	-8	54	4.69
B	PCu	7	0	-72	58	4.64
L	DC		-20	-92	-24	4.62
R	LG	18	4	-96	-2	4.36
L	islC		-34	-62	-40	4.34
R	PreCG	6	36	-6	38	4.28
L	dlPFC	9	-34	32	45	4.20
R	aINS	13	36	16	-4	4.05
L	MFG	6	-32	2	60	4.02
L	MTG	37	-48	-42	-10	4.02
L	FP	10	-26	52	-8	4.00
R	IFG	45	46	20	8	3.96
L	aINS	13	-32	-22	6	3.96
L	islC		-40	-78	-42	3.93
L	mCC	24	-6	0	26	3.92
L	PreCG	6	-52	-4	14	3.90
R	STG	38	46	-2	-18	3.90
L	ITG	37	-60	-62	-14	3.86
L	aINS	13	-36	12	6	3.85
L	FP	10	-26	48	20	3.84
R	FP	10	30	66	4	3.84
R	Thal		20	-10	18	3.77
R	Thal		22	-22	12	3.71
R	PostCG	3	50	-14	26	3.70
R	OP	18	30	-84	-20	3.66
L	STG	22	-48	-4	-6	3.63
R	GP		20	-2	2	3.62
R	STG	22	62	4	2	3.61
L	MFG	6	-30	-4	40	3.59

Table 3.3 (continued)

L	PC		-26	-68	-26	3.58
R	islC		24	-78	-48	3.39
L	SFG	6	-22	24	56	3.33
R	TC		54	-60	-30	3.27
L	PostCG	3	-36	-28	64	3.22
L	CC		-30	-38	-36	3.22
L	Thal		-10	-22	12	3.20
L	PCu	19	-28	-78	46	3.16
R	aIPL	40	52	-28	36	3.16
R	FG	37	56	-60	-14	2.86

Note. aINS = Anterior insula, aCC = Anterior cingulate cortex, CC = Culmen of the cerebellum, DC = Declive of the cerebellum, FG = Fusiform gyrus, FP = Frontal pole, GP = Globus pallidus, islC = Inferior semilunar lobule of the cerebellum, ITG = Inferior temporal gyrus, LG = Lingual gyrus, mCC = Midcingulate cortex, OP = Occipital pole, PC = Pyramis of the cerebellum, PreCG = Precentral gyrus, SFG = Superior frontal gyrus, STG = Superior temporal gyrus, TC = Tuber of the cerebellum, Thal = Thalamus. Other abbreviations can be found in the Table 3.2 note.

In contrast, outcome simulations were associated with increased BOLD signal in bilateral medial prefrontal cortex, inferior frontal gyrus, and amygdala (see Table 3.4 and Figure 3.4).

Table 3.4

Peak regions of activation for Outcome simulation > Process simulation

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
Outcome simulation > Process simulation						
R	mPFC	9	8	58	20	4.81
L	IFG	47	-28	30	-10	4.21
B	aCC	24	-2	22	10	3.99
L	AMG		-20	-6	-14	3.96
L	IFG	46	-48	38	0	3.78
L	mPFC	9	-10	58	28	3.72
L	IFG	45	-56	22	18	3.52
R	IFG	46	50	36	8	3.47
R	AMG		16	-2	-20	3.18

Note. AMG = amygdala. Other abbreviations can be found in previous Tables' notes.

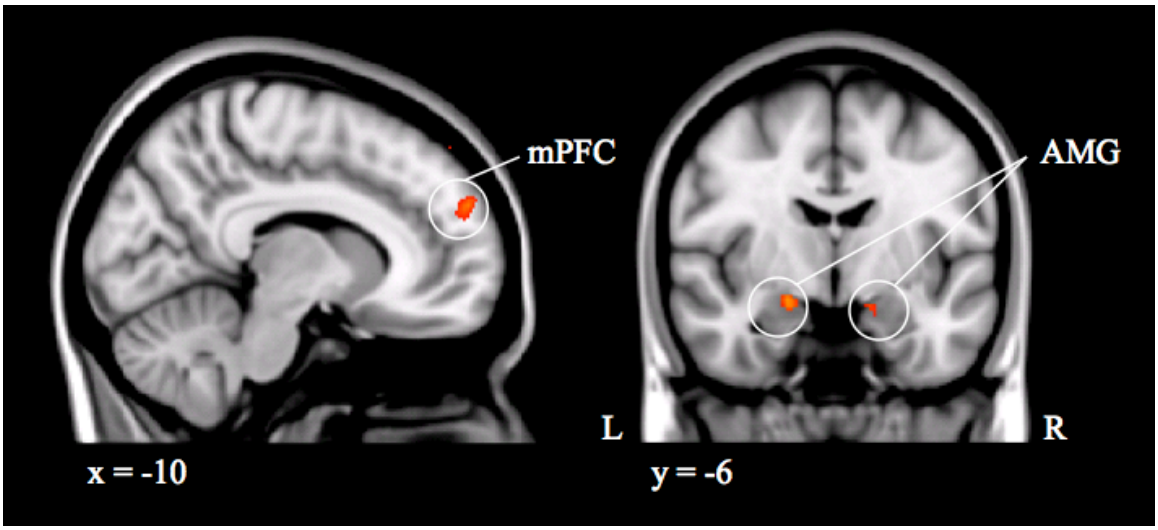

Figure 3.4. Outcome simulation > Process simulation. Activations in regions of the default network (medial prefrontal cortex) and of the limbic system (bilateral amygdala).

The secondary PLS analysis of process and outcome simulations with different numbers of steps and events tested whether the number of imagined steps/events modulated neural activity. Its results closely resembled those of the previous analysis: The first LV dissociated both simulation conditions from the odd/even condition, accounting for 75% of the variance ($p < .001$), while a significant second LV dissociated process from outcome simulations and explained 9% of the variance ($p = .03$) but did not differentiate between conditions with different numbers of steps or events. Even a separate PLS analysis comparing only process simulations with 2, 3, or 4 imagined steps did not reach significance (LV accounting for 60% of the covariance in the data, $p = .07$). An analogous analysis of outcome simulations with different numbers of events rendered no significant LV (accounting for 55% of the variance; $p = .25$).

Task-related functional connectivity

The seed PLS analysis for process simulations resulted in a significant pattern of task-related functional connectivity with one significant latent variable that accounted for 53% of the covariance ($p < .001$). Activity in bilateral dlPFC, aIPL, and pCC seeds was significantly

correlated with the whole-brain pattern, and the five seed regions reliably covaried together (see Figure 3.5).

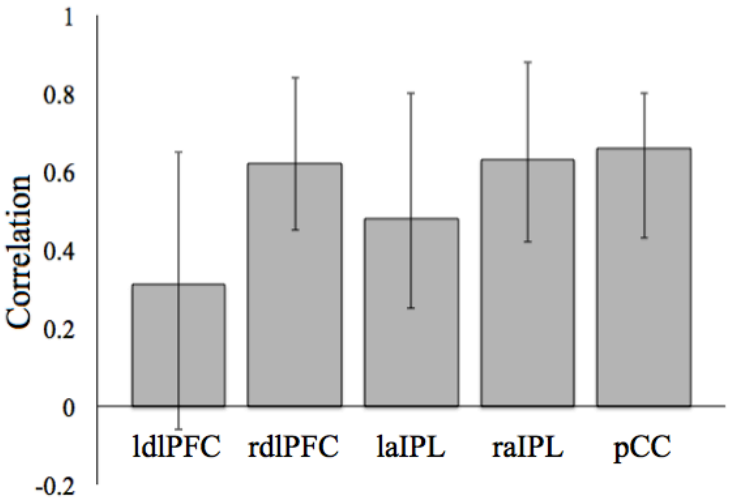

Figure 3.5. Correlations of activity in bilateral dlPFC, aIPL, and PCC with their respective brain scores show how activity in the five seeds covaries with activity in the entire network. Error bars represent 95% bootstrapped confidence intervals, which indicate no significant differences in the pattern of connectivity between the five seed regions.

The regions that were functionally connected with the seeds during process simulations were part of the default network, such as mPFC, IFG, and medial temporal lobe, as well as the frontoparietal control network, such as MFG, rlPFC, and PCu (see Table 3.5 and Figure 3.6).

Table 3.5

*Peak regions functionally connected with posterior cingulate cortex, bilateral anterior inferior parietal lobules, and bilateral dorsolateral prefrontal cortex seeds during process simulations***.**

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
L	dlPFC	9	-32	58	24	7.32
R	dlPFC	9	44	42	28	7.13
L	IPL	13	-44	-46	28	6.47
L	PC		-14	-86	-28	6.35

Table 3.5 (continued)

L	pCC	31	-14	-44	34	6.34
L	aCC	32	-6	20	34	6.34
R	aIPL	40	46	-54	54	6.07
R	mCC	24	2	-18	42	5.93
R	CT		22	-64	-42	5.84
L	Med		-4	-48	-50	5.80
R	MFG	6	18	16	56	5.73
L	PreCG	6	-26	-6	68	5.71
R	CT		12	-58	-32	5.59
R	pCC	29	6	-42	10	5.56
R	PHG	34	24	2	-16	5.48
L	MFG	8	-36	28	40	5.42
R	Caud		12	8	18	5.40
L	TP	38	-50	14	-12	5.36
R	IFG	13	44	30	2	5.30
L	islC		-32	-74	-46	5.28
L	PHG	23	-18	2	-18	5.20
R	MOG	18	36	-76	10	5.15
L	PHG	19	-24	-50	-10	5.10
R	islC		12	-76	-40	5.07
R	STG	41	46	-30	2	5.04
L	PreCG	6	-46	-6	24	5.04
L	PreCG	4	-42	-12	42	5.03
R	Thal		4	-16	6	4.93
R	PHG	27	36	-26	-12	4.88
R	FG	37	42	-60	-20	4.80
L	PARC	6	-2	-30	70	4.72
L	PCu	7	-8	-64	40	4.67
R	PCu	19	32	-70	34	4.65
L	MOG	19	-30	-82	18	4.61
B	CUN	18	0	-78	24	4.51
R	MTG	20	58	-38	-12	4.49
R	FP	8	34	36	48	4.41
L	CT		-38	-56	-48	4.38
R	Mid		10	-16	-14	4.31
L	IFG	9	-38	12	24	4.29
R	IFG	9	40	14	22	4.23
R	IFG	45	60	30	4	4.10
L	MTG	21	-60	-30	-16	4.08
L	MOG	19	-52	-74	-2	4.05

Table 3.5 (continued)

B	CUN	18	0	-78	24	4.51
R	MTG	20	58	-38	-12	4.49
R	FP	8	34	36	48	4.41
L	CT		-38	-56	-48	4.38
R	Mid		10	-16	-14	4.31
L	IFG	9	-38	12	24	4.29
R	IFG	9	40	14	22	4.23
R	IFG	45	60	30	4	4.10
L	MTG	21	-60	-30	-16	4.08
L	MOG	19	-52	-74	-2	4.05
R	PCu	7	16	-70	36	4.04
R	STG	42	70	-30	14	3.99
R	PreCG	6	40	0	26	3.99
L	msFG	6	-4	-4	72	3.98
R	CT		42	-52	-36	3.94
R	PCu	7	6	-64	40	3.76
L	INS	13	-34	-24	4	3.72
L	LN		-14	-2	4	3.59

Note. CUN = Cuneus, INS = Insula, LN = Lentiform nucleus, Med = Medulla, Mid = Midbrain, MOG = Middle occipital gyrus, msFG = Medial superior frontal gyrus, PARC = Paracentral lobule, TP = Temporal pole. Other abbreviations can be found in previous Tables' notes.

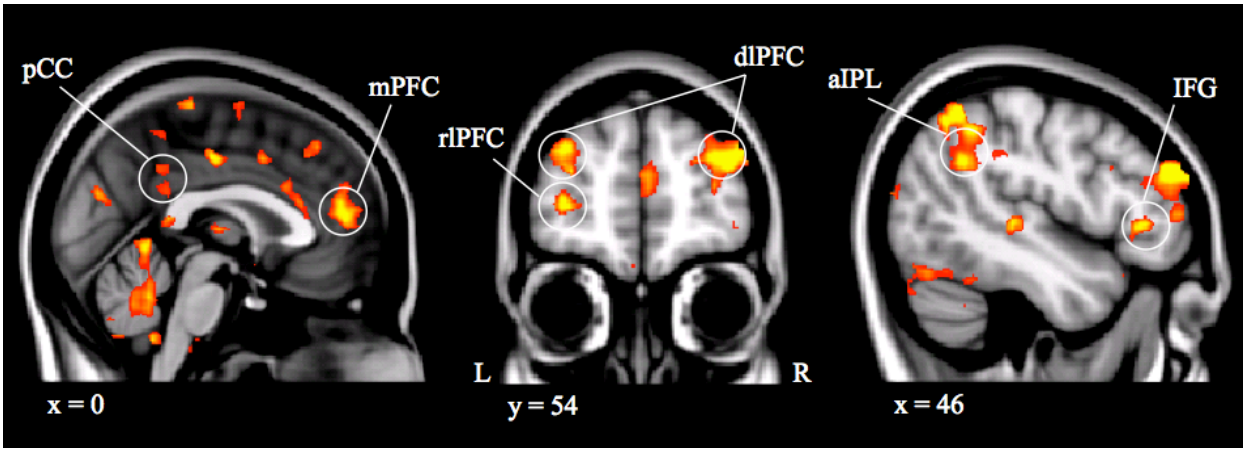

Figure 3.6. Regions of the distributed functional network in the seed PLS analyses of process simulations.

For outcome simulations, one significant LV accounted for 51% of the variance (p = .01) in the seed PLS analysis. The two amygdala seeds and the mPFC seed reliably covaried together and were significantly correlated with the composite whole-brain score (see Figure 3.7).

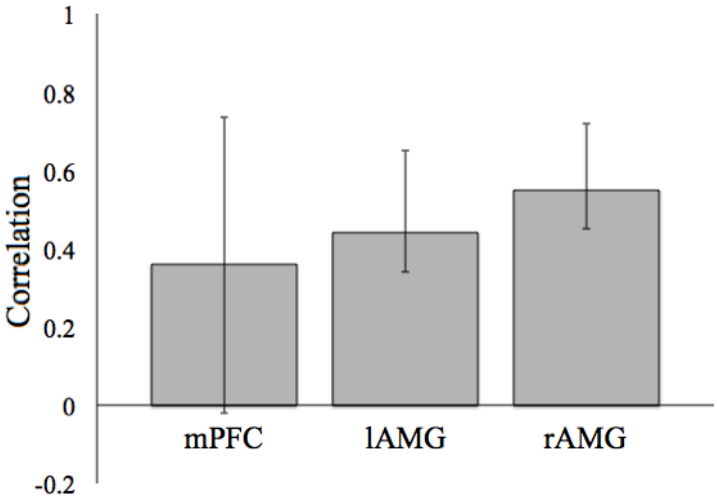

Figure 3.7. Correlation of activity in mPFC and bilateral amygdala seeds with their respective brain scores show how activity in the three seeds covaries with activity in the entire network. Error bars represent 95% bootstrapped confidence intervals, which indicate no significant differences in the pattern of connectivity between the three seed regions.

The resulting functional network included vmPFC, rsC and medial temporal lobe regions that are commonly associated with the default network (see Table 3.6 and Figure 3.8). Regions that have been implicated in reward processing were also functionally recruited during outcome simulations, including NAcc, aCC, caudate, thalamus, MFG, and vmPFC (Liu, Hairson, Schrier, & Fan, 2011).

Table 3.6

Peak regions functionally connected with medial prefrontal cortex and bilateral amygdala seeds during outcome simulations

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
R	AMG		16	-2	-16	9.60
R	LG	19	26	-72	4	9.18
L	PHG	28	-18	-18	-20	8.49
R	CC		24	-32	-34	8.35
L	LG	19	-28	-70	4	8.23
L	SPL	7	-24	-66	56	7.58
L	DC		-20	-70	-20	7.36
L	Med		-2	-30	-44	7.28
R	Caud		18	-10	22	7.21
R	FG	37	46	-60	-20	6.82
L	Caud		-14	10	22	6.81
L	rsC	29	-2	-36	0	6.38
L	Pons		-10	-24	-24	6.36
L	LN		-16	0	-4	6.19
R	OP	18	2	-98	18	6.16
R	Pons		4	-42	-30	5.99
R	FG	19	22	-54	-10	5.96
L	aCC	32	-2	22	32	5.94
L	aCC	32	-2	36	20	5.75
R	PCu	7	2	-72	56	5.62
L	msFC	6	-2	28	66	5.55
L	FP	10	-32	46	12	5.37
L	TC		-34	-80	-26	5.29
R	Thal		26	-26	10	5.17
L	Put		-30	4	14	5.14
R	NAcc		12	10	-10	5.06
R	MFG	6	2	8	52	4.99
L	LG	18	-2	-64	2	4.80
L	HC		-40	-34	-6	4.77
L	Thal		-26	-32	8	4.73
R	SPL	7	22	-58	68	4.66
L	PCu	7	-8	-56	74	4.66
L	STG	22	-46	-20	-8	4.61
R	SOG	19	42	-74	38	4.60
L	CT		-18	-42	-50	4.52
L	MFG	9	-28	34	30	4.42

Table 3.6 (continued)

B	vmPFC	10	0	56	0	4.40
R	PreCG	4	28	-24	72	4.36
R	aCC	32	8	14	38	4.35
B	mPFC	8	0	36	40	4.25
L	FP	10	-12	64	20	4.21

Note. HC = Hippocampus, Put = Putamen, SOG = Superior occipital gyrus, SPL = Superior parietal lobule. Other abbreviations can be found in previous Tables' notes.

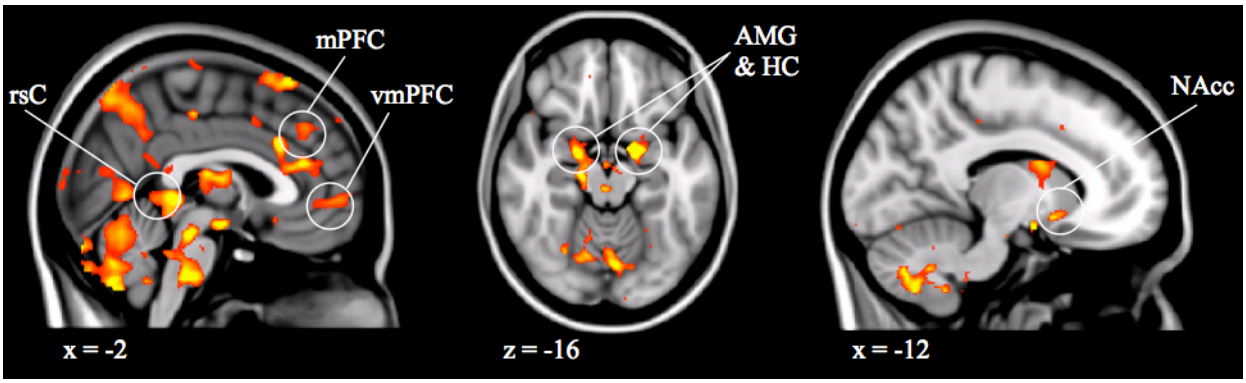

Figure 3.8. Regions of the distributed functional network in the seed PLS analysis of outcome simulations.

Discussion

The present study examined the neural correlates of our ability to imagine a series of steps leading up to a goal and to simulate what it would be like to achieve a goal. Participants engaged in process simulations, during which they imagined a number of steps they would take toward achieving a given goal. This task required them to project themselves into the future, generate a number of plausible steps, put them into a coherent sequence, and simulate themselves going through these steps, all the while keeping in mind the end goal. Process simulations recruited default network as well as frontoparietal control network regions, which converged with evidence from fMRI studies of related planning and problem-solving simulations (Gerlach, et al., 2011; Spreng et al., 2010). Components of the frontoparietal network, such as dlPFC, have

been linked to cognitive control (e.g., Badre & D'Esposito, 2007; Botvinick, 2008; Packer & Cunningham, 2009) and executive planning processes in both healthy samples (e.g., Baker et al., 1996; Burgess et al., 2000; Rowe et al., 2001) and lesion patients (e.g., Goldstein et al., 1993; Luria, 1966; Morris & Ward, 2005). DlPFC activity was not correlated with information load, suggesting that the involvement of executive processes cannot be accounted for by increasing task demands. Many recent findings have provided evidence that the default network supports self-projection and prospection (Andrews-Hanna, 2012, Buckner & Carroll, 2007; Spreng & Grady, 2010), and that pCC acts as one of its critical connector hubs (Buckner et al., 2009; Fransson & Marrelec, 2008; Hagman et al., 2008). Our seed PLS analysis confirmed that defining nodes of the default and frontoparietal control networks (pCC, aIPL, and dlPFC) behaved as a functional network during process simulations and were connected with a distributed network of regions that consisted of other default and frontoparietal control network regions, including MFG, IFG, rlPFC, PCu, and PHG. These findings provide more evidence that the default and frontoparietal control network are coactive during goal-directed simulations that require cognitive control (Spreng, 2012). The results fit with the hypothesized role of the frontoparietal control network, which is thought to regulate activity in the default network and the dorsal attention network, whose activation has been linked to exogenous stimuli (Corbetta & Shulman, 2002; Gao & Lin, 2012; Smallwood, Brown, Baird, & Schooler, 2012; Spreng et al., 2010). In the present task, the frontoparietal control network likely shielded the default network from distracting exogenous stimuli and supported the simulation of complex internal plans.

During outcome simulations, participants imagined what it would be like to achieve a given goal. They were prompted to generate and imagine themselves in a number of events they associated with reaching a goal, which allowed them to pre-experience the affective impact that

these events could have on them. Compared to process simulations, we found outcome simulations to be associated with increased activity in mPFC, a main node of the default network (e.g., Andrews-Hanna, Reidler, Sepulcre, et al., 2010; Buckner et al., 2008), and the amygdala, a region that has consistently been linked to emotion processing (e.g., Bechara et al., 1999; 2003). Across many studies, medial prefrontal cortex has shown increased activation in response to self-referential processing (e.g., Jenkins & Mitchell, 2007; Macrae et al., 2004; Mitchell, Schirmer, Ames, & Gilbert, 2011), including thinking about personal compared to nonpersonal future goals (D'Argembeau et al., 2010). Participants in the current study were significantly more likely to consider a given goal for which they had generated outcome simulations a personal future goal and also rated it higher in importance and desirability. These ratings may be explained by the reward-emphasizing nature of outcome simulations, which might have led participants to identify more with the goals whose achievement they imagined.

A functional connectivity analysis confirmed that mPFC activity was significantly correlated with bilateral amygdala activity during outcome simulations, and that the three seed regions were also connected to a distributed network of regions consisting of other default network regions (e.g., vmPFC, rsC, HC) and regions involved in the anticipation and evaluation of rewards and outcomes, including aCC, NAcc, MFG, caudate, and medial thalamus (e.g., Peters, J., & Büchel, 2010ab; Liu et al., 2011; Schulz, 2000). Activation in the mPFC seed region has been linked to imagining positive events and goals that promoted positive actions (D'Argembeau et al. 2008; Packer & Cunningham, 2009; Sharot et al., 2007) and to evaluating possible rewards and outcomes (Benoit et al., 2011; Liu et al., 2011; Montague, King-Casas, & Cohen, 2006; Rushworth & Behrens, 2008). Other components of the reported functional network, such as aCC, amygdala, and the hippocampus, have been shown to be coactive when

participants envisioned possible rewards, with the effect of alleviating reward delay discounting (Peters & Büchel, 2010a). Finally, vmPFC is presumed to play a role in the ability to anticipate future consequences and to decide on goals to pursue (Bechara et al., 1994; Eslinger & Damasio, 1985), which aligns with its recruitment during outcome simulations. The present findings reveal how default network and reward-processing regions can act together to generate simulations of desired future outcomes, thereby facilitating decision-making about future goals.

Our results provide further evidence of the default network's involvement in goal-directed episodic simulations and its ability to flexibly pair with both frontoparietal control and reward-processing regions to support such simulations. It is also useful to consider our findings in the context of the adaptive value of process and outcome simulations. Behavioral studies of process and outcome simulations have suggested that both types of simulation can help us achieve goals but may do so in different ways (e.g., Benoit et al. 2011; Taylor & Pham, 1999). While process simulations may aide the implementation of plans to reach a goal by laying out the exact steps necessary to achieve it, outcome simulations may help us choose beneficial long-term goals if, for example, the ability to make far-sighted decisions in the context of temporal discounting (Benoit et al., 2001; Peters & Büchel, 2010a) extends to the choice of personal goals. However, the exact mechanisms behind these potential benefits have to be explored further. By providing initial insights into the brain networks that subserve process and outcome simulations, the current study has helped to lay the groundwork for further behavioral and neuroimaging investigations.

Paper 3:

Gerlach, K. D., Dornblaser, D. W., & Schacter, D. L. (in press). Adaptive constructive processes and memory accuracy: Consequences of counterfactual simulations in young and older adults. *Memory*.

Abstract

People frequently engage in *counterfactual thinking*: mental simulations of alternative outcomes to past events. Like simulations of future events, counterfactual simulations serve adaptive functions. However, future simulation can also result in various kinds of distortions and has thus been characterized as an *adaptive constructive process*. Here we approach counterfactual thinking as such and examine whether it can distort memory for actual events. In Experiments 1a/b, young and older adults imagined themselves experiencing different scenarios. Participants then imagined the same scenario again, engaged in no further simulation of a scenario, or imagined a counterfactual outcome. On a subsequent recognition test, participants were more likely to make false alarms to counterfactual lures than novel scenarios. Older adults were more prone to these memory errors than younger adults. In Experiment 2, younger and older participants selected and performed different actions, then recalled performing some of those actions, imagined performing alternative actions to some of the selected actions, and did not imagine others. Participants, especially older adults, were more likely to falsely remember counterfactual actions than novel actions as previously performed. The findings suggest that counterfactual thinking can cause source confusion based on internally generated misinformation, consistent with its characterization as an adaptive constructive process.

Adaptive constructive processes and memory accuracy:

Consequences of counterfactual simulations in young and older adults

"If only I'd gone to bed earlier last night, I could've woken up on time and wouldn't have had to rush out of the house" describes a scenario many of us have probably envisioned before. People frequently engage in *counterfactual thinking* by flexibly reshaping their memory of past events and constructing mental simulations of how past events might have turned out differently (e.g., Byrne, 2005; Epstude & Roese, 2008; Roese, 1997). Counterfactual thinking can provide a more positive alternative to a past event, referred to as an *upward counterfactual*, such as the above scenario, or it can represent a more negative reality, referred to as a *downward counterfactual* ("If I'd gone to bed even later, I might've slept through my alarm and missed an important appointment"). Counterfactual thinking occurs more often following negative or unusual rather than positive events (Roese & Hur, 1997; Roese & Morrison, 2009): simulations tend to involve idealistic upward rather than downward counterfactuals.

Simulating such upward counterfactuals often elicits feelings of disappointment or regret, whereas downward counterfactuals tend to evoke feelings of relative satisfaction or relief by suggesting that a past event could have had a worse outcome (e.g., Roese, 1997; Wrosch et al., 2005). Prevailing functional theories of counterfactual thinking (e.g., Epstude & Roese, 2008; Markman & McMullen, 2005; Roese & Morrison, 2009) posit that its purpose is to prepare us for future actions and goals by way of emotion and behavior regulation that improves future performance (e.g., Ciarocco et al., 2010; Galinsky & Kray, 2004; Markman et al., 2008). Upward counterfactual thinking in particular appears to trigger adaptive behaviors by allowing participants to very quickly form intentions for improved future behavior (Smallman & Roese, 2009), which in turn help initiate the desired behavior (Brandstätter, Lengfelder, & Gollwitzer,

2001). Nasco and Marsh (1999) demonstrated this adaptive effect of counterfactual thinking in a study that followed students' performance on an exam: they found that the tendency to generate counterfactuals was positively correlated with students' subsequent performance-enhancing behavior, sense of control, and improved grades.

These adaptive consequences of counterfactual simulations resemble adaptive effects associated with constructing simulations of possible future events. Recent research on the process termed *episodic future thinking* (Atance & O'Neil, 2001) or *episodic simulation* (Schacter et al., 2007, 2008) has shown that constructing simulations of experiences that might occur in one's personal future depends on many of the same processes as remembering actual past experiences (for recent reviews, see Schacter et al., 2012; Szpunar, 2010). Such simulations serve a number of useful functions (Schacter, 2012; Suddendorf & Corballis, 2007), including contributing to goal-directed planning (e.g., Gollwitzer, 1999; Spreng et al., 2010; Taylor et al., 1998) and problem solving (e.g, Sheldon, McAndrews, & Moscovitch, 2011; Gerlach et al., 2011), enhancing subsequent memory (e.g., Klein, Roberston, & Delton, 2010, 2011; Martin, Schacter, Corballis, & Addis, 2011), promoting farsighted decision making (e.g., Benoit et al., 2011; Peters & Büchel, 2010a), and contributing to psychological well-being (e.g., Brown et al., 2002; Sharot et al., 2007; Szpunar, Addis, & Schacter, 2012). However, such simulations may also be associated with a variety of pitfalls (Schacter, 2012), including inaccurate predictions of future happiness (Gilbert & Wilson, 2007), instability over time resulting in inflated prediction of the likelihood or plausibility of future events (e.g., Koehler, 1991; Szpunar & Schacter, in press), vulnerability to the planning fallacy (Dunning, 2007), and possible confusions between imagined and actual events (e.g., Garry et al., 1996; Goff & Roediger, 1998; M. K. Johnson, 2006, 1998; Loftus, 2003). These considerations led Schacter (2012) to propose that episodic

simulation of future events constitutes an adaptive constructive process: it plays a functional role in memory and cognition but creates distortions, biases, or illusions as a consequence of doing so (see also, Bartlett, 1932; Brainerd & Reyna, 2005; Howe, 2011; Johnson & Sherman, 1990; Newman & Lindsay, 2009; Roediger, 1996; Schacter & Addis, 2007; Schacter, Guerin, & St. Jacques, 2011).

Here we suggest that counterfactual thinking – more specifically, *episodic counterfactual thinking* (De Brigard & Giovanello, 2012; De Brigard, Addis, Ford, Schacter, & Giovanello, in press) about specific past personal experiences – can also be viewed as an adaptive constructive process. Like other adaptive constructive processes, episodic counterfactual thinking not only helps cognition and behavior as outlined earlier, but it can also create biases and distortions. Early studies of counterfactual thinking focused on its effect on judgment, demonstrating that the more salient an imagined alternative to a past event was, the more it tended to alter participants' sympathies toward those involved in the event, resulting in biased judgment of their actions (e.g., Gleicher et al., 1990; Kahneman & Tversky, 1982; Macrae, 1992; Miller & McFarland, 1986). In the clinical literature, excessive counterfactual thinking has been linked to increased anxiety and distress (Gilbar & Hevroni, 2007, Markman et al., 2008; Nolen-Hoeksema, 2000).

Although counterfactual thinking is pervasive and seemingly automatically triggered in many everyday situations, its role as an adaptive constructive process has not been examined with regard to memory. For example, it is unclear whether imagining an alternative outcome to a past event could affect a person's memory of the original event by either enhancing the memory of the original event, which is evoked every time a person simulates its counterfactual outcome, or by possibly distorting a person's memory of the original event by rendering the counterfactual outcome more salient. As noted earlier, previous research has shown that imagining novel events

can produce memory confusion, leading a person to consider the past occurrence of the simulated event as more likely, or to recollect it as a 'real' memory (e.g., Garry et al., 1996; Loftus, 2003; Mazzoni & Memon, 2003). If complex events are imagined repeatedly, they tend to be experienced vividly, thus making it difficult to distinguish between memories of real events and imagination (Goff & Roediger, 1998; M. K. Johnson, 2006). Such source attribution errors occur when a person remembers an event but either confuses the memory of a simulation with the memory of a real event, or fails to recall the source of the memory entirely.

Even though one recent study found that a specific type of counterfactual thinking, in which participants only focus on an imagined positive alternative irrespective of reality, can lead to an overestimation of past performance in a game of blackjack (Petrocelli & Crysel, 2009), no studies have examined whether episodic counterfactual simulations – that is, counterfactual simulations of the outcomes of specific experiences – can distort episodic memories of those experiences. If episodic counterfactual thinking has an effect on episodic memory, it might function as a form of internally generated misinformation. A large body of research has documented that exposure to misinformation provided by an experimenter can affect memory (Loftus, 2005), ranging from leading questions that create false eyewitness memories (Loftus, 1979) to planting false memories of an event that never occurred using photographs (Schacter, Koutstaal, Johnson, Gross, Angell, 1997). Meade and Roediger (2006) have shown how *self*-generated misinformation on a forced recall test can also lead to false recollection: Participants who guessed words on an initial forced recall test of word lists tended to falsely recollect those guesses as memories of the original material on subsequent tests. In the case of episodic counterfactual thinking, the misinformation could comprise a self-generated alternative outcome to a past event. Counterfactual simulation could render the alternative outcome similarly

plausible, elaborate, and available to be retrieved as the original event, which in turn would likely produce confusion between the memory of the original event and the counterfactual event that was simulated after the fact.

However, unlike in typical misinformation paradigms, episodic counterfactual simulations are generated as a direct consequence of an experience, which could tie them to the original experience to such an extent that their memory might automatically evoke the original event, which could prevent any confusion. Constructing counterfactual simulations requires a person to contrast the past event with the counterfactual outcome, thereby underlining their differences and at the same time creating a link between the memory of the original event and the counterfactual. Feelings of regret, disappointment, or relief about the original event that are brought about by the counterfactuals could further improve memory for the original event.

We propose to investigate the effects of episodic counterfactual thinking on memory in both younger and older adults. Older adults often exhibit heightened susceptibility to memory distortions that involve confusion between events that were imagined and events that were perceived or performed (e.g., Hashtroudi, Chrosniak, & Johnson, 1990; McDaniel, Lyle, Butler, & Dornburg, 2008), as well as between perceived events and post-event information (e.g., Jacoby, Bishara, Hessels, & Toth, 2005; Remy, Taconnat, & Isingrini, 2008; Roediger & Geraci, 2007). Compared to younger adults, older adults also appear to be more affected by the aforementioned misinformation effect of self-generated guesses on a word recall test, which were subsequently falsely recalled or recognized as actual memories (Huff, Meade, & Hutchison, 2011; Meade & Roediger, 2006; Meade & Roediger, 2009*;* Meade, Geraci, & Roediger, 2012). Whether or not this age-related susceptibility to memory distortions applies to counterfactual simulations of past events is unknown, but the aforementioned studies provide grounds for

hypothesizing that engaging in episodic counterfactual simulations about how past events might have turned out differently could produce greater memory distortion in older than younger adults.

Examining the effects of episodic counterfactual simulation on memory distortion in both younger and older adults is also of interest in light of the distinction between upward and downward counterfactuals. For instance, negative past events may be perceived as even more negative when people remember them after they have simulated what they should have, yet did not do, during the original event. Downward counterfactual thinking, in contrast, may lead people to judge the emotional valence of a past event to be more positive by emphasizing that "it could have been worse than it was". Older adults frequently exhibit a positivity effect, remembering relatively more positive information, compared with negative or neutral information, than do younger adults (e.g., Mather & Carstensen, 2005). These observations suggest that older adults may be especially vulnerable to distorting effects of downward counterfactuals, which may enhance positive feelings about the actual event outcome, as compared with upward counterfactuals, which may enhance negative emotions about the outcome of the event. We were particularly interested in these questions involving aging because counterfactual thinking is common across the lifespan (e.g., Epstude & Roese, 2008).

To examine possible effects of counterfactual simulation on episodic memory in both younger and older adults, we developed two novel paradigms that combined new materials with established procedures for testing memory. Experiments 1a and 1b examined counterfactual simulations based on imaginary scenarios, and Experiment 2 examined counterfactual simulations of actions that participants performed in the laboratory.

Experiments 1a/1b

In Experiment 1a, we aimed to approximate real-life experiences and processes of counterfactual thinking in the laboratory while maintaining experimental control. Participants imagined themselves experiencing brief everyday scenarios describing situations with either a positive or a negative outcome that motivated subsequent upward or downward counterfactuals. After this encoding phase, we introduced the critical manipulation: For a subset of the scenarios, participants imagined counterfactual outcomes to previously presented scenarios. For the remaining scenarios, participants either imagined the same scenario again or engaged in no simulation. Following a delay, participants performed a recognition memory test, in which initially experienced scenarios were to be categorized as old, and novel scenarios as well as scenarios that had been simulated as alternatives to initially presented scenarios were to be categorized as new. We hypothesized that if engaging in counterfactual simulations of how past events might have turned out differently distorts memory for the original experience, then participants should be more likely to make false alarms (incorrectly identify new items as old) to counterfactual lures than to novel items.

In Experiment 1b, we altered the scenarios to be more extreme in their emotional valence. Our aim was to test whether effects found in Experiment 1a with less arousing, everyday scenarios extended to more emotionally arousing situations, and to explore whether upward and downward counterfactuals of such situations might differentially affect memory.

Method

Participants

For Experiment 1a, we tested 24 younger adults (15 female; M_{age} = 22 years, SD_{age} = 3.9) between the ages of 18 and 34 and 24 older adults (15 female; M_{age} = 73.5 years, SD_{age} = 6.2)

between the ages of 62 and 82. For Experiment 1b, we collected data from 24 younger adults (15 female; M_{age} = 23 years; SD_{age} = 4.4) between the ages of 18 and 34 and from 24 older adults (16 female; M_{age} = 71 years; SD_{age} = 4.7), whose age ranged from 62 to 81 years old. Younger adults were recruited through the Harvard University Psychology Study Pool, and older adults were initially recruited from the Boston area community through flyers, newspaper advertisements, and word of mouth. All older participants were screened for dementia and geriatric depression. Older adults who participated in the experiment scored at least 27/30 on the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975), 30/75 on the logical memory score of the Wechsler Memory Scale-III (Wechsler, 1997), and lower than 5/14 on the Geriatric Depression Scale (Scogin, 1987). All participants were native English speakers with normal or corrected-to-normal hearing and vision, had no history of neurological or psychiatric illness, and had at minimum a high-school education. Participants gave informed consent in accordance with the guidelines of the Harvard University Committee on the Use of Human Subjects.

Materials

The stimulus set for Experiment 1a consisted of 120 brief scenarios describing everyday situations, each of which had a version with a more positive and a version with a more negative outcome. For Experiment 1b, these scenarios were altered to be more extreme in their emotional valence (for examples, see Fig. 4.1A). Emotional valence was validated for both stimulus sets using a 7-point scale that instructed raters to indicate how they felt when they imagined themselves in each scenario (1 = *very bad*, 4 = *neutral*, 7 = *very good*).

The scenarios for both stimulus sets were between 2 to 4 sentences long; positive and negative versions of a scenario were matched in length. All scenarios were read and audio-recorded by a male native speaker of English (audio clips were 8-22 s long) and were presented

to participants over headphones (Sennheiser HD 280 Pro). In addition, a conditional clause of the format "If A had/had not happened, then the different outcome B could/would/might have occurred" was recorded for each version of a scenario to be used for the counterfactual manipulation. The alternative outcome ("outcome B") suggested in the conditional clause always described the opposite-valence version of the scenario (see Fig. 4.1B).

	Experiment 1a		**Experiment 1b**	
A. Encoding	**Positive**	**Negative**	**Positive**	**Negative**
	"You're at a nearby furniture store to buy a new chair for your kitchen table to replace a chair whose leg broke. You measured the height of your table and find a chair whose design fits in well enough and whose height matches the table. You carry it home and replace the broken chair with it."	"You're at a nearby furniture store to buy a new chair for your kitchen table to replace a chair whose leg broke. You don't quite remember how high your kitchen table is but buy a chair whose design seems to fit perfectly. When you get home, you find that the chair is too high for your table."	"You're at a furniture store that's an hour away to buy a new chair for your kitchen table to replace a chair whose leg broke. You measured the height of your table and find a chair you think fits well. The chair even turns out to be on sale, and you come back home to find that the chair matches the table and the other chairs perfectly."	"You're at a furniture store that's an hour away to buy a new chair for your kitchen table to replace a chair whose leg broke. You don't quite remember how high your kitchen table is but buy a chair you think fits well. When you get home after an hour drive, you try it out to find that it's too high and that its back and two legs are loose."
B. Imagination	**Downward Counterfactual**	**Upward Counterfactual**	**Downward Counterfactual**	**Upward Counterfactual**
	"If you hadn't measured the height of your kitchen table when buying a new chair, you could've found a chair whose design fit perfectly, but when you got home, you might've found out that the chair was too high for the table."	"If you'd measured your kitchen table before buying a new chair at the furniture store, you could've found a chair whose design and height matched the table better. You would've carried it home and replaced the broken chair."	"If you hadn't measured the height of the table to make sure the new chair matched in size, you could've driven an hour back home. When you tried it out, you could've found that the new chair was too high and that its back and two legs were loose.	"If you'd measured the height of your table before driving an hour to the furniture store, you could've found a fitting, functional chair. It might've even been on sale, and you could've come back home with a perfectly matching chair.

Figure 4.1. A. Examples of positive and negative versions of a scenario presented during the encoding phase in Experiments 1a and 1b. B. Examples of upward and downward counterfactuals derived from the scenarios in A. that are presented during the simulation phase in Experiments 1a and 1b.

Each scenario was paired with a postcard-size color photo that applied to both the positive and negative version of the scenario and did not give away the outcome of a scenario. Pictures were selected to represent real-life scenes, which did not contain any people that were actors in a scenario. Only a few pictures had strangers in the background as part of an urban scene. We imposed these criteria onto our set of visual stimuli to facilitate participants' ability to use each scene as a backdrop for their own imagination and to allow their mental simulations to be as vivid as possible.

Design and Procedure

The overall design corresponded to a 2 (age: young, old) x 2 (valence: positive, negative) x 3 (condition: Identical, Counterfactual, No simulation) mixed factorial, where age was the between-subjects factor and valence and condition were the within-subjects factors.

Encoding phase. The laboratory experiment consisted of a two-phase study period and a subsequent memory test. To ensure that participants understood all instructions and were able to simulate the proposed scenarios for the stipulated period of time, each phase of the experiment was preceded by two practice trials. During the encoding phase of the study period, participants listened to and imagined themselves in all 120 scenarios, which were presented in random order as 5 blocks of 24 scenarios with the same number of positive and negative scenarios per block. Participants were only presented with one version of each scenario; positive and negative versions of a scenario were counterbalanced across participants. While listening to a scenario, participants viewed a related picture to provide them with a visual context for their imagination and to make the encoding phase more salient. To allow equal encoding time for each visual stimulus, pictures remained on screen for 23 s, which exceeded the duration of the longest sound

clip by 1 s, and participants were instructed to imagine themselves in the situation for as long as the picture was on the screen.

After viewing a scenario, participants rated how they felt when they imagined themselves experiencing the scenario on a 7-point scale (1 = *very bad*, 4 = *neutral*, 7 = *very good*). They also rated whether they had ever had the same or a very similar experience (1 = *definitely not*, 4 = *undecided*; 7 = *definitely yes*) and how likely they thought it was that they would experience the scenario in the future (1 = *very unlikely*, 4 = *undecided*; 7 = *very likely*). All ratings were self-paced throughout the experiment. It took participants approximately an hour and fifteen minutes to complete the encoding phase; they were allowed to take short breaks between each of the five experimental blocks. At the end of the encoding phase, participants were given 10 min to complete a beginners' Sudoku puzzle as an unrelated distractor task.

Simulation phase. During the subsequent simulation phase, which lasted about 45 min with breaks in between blocks, participants listened to 40 scenarios (20 positive, 20 negative) from the encoding phase (Identical simulation condition) and 40 counterfactual conditionals that were related to scenarios from the encoding phase (Counterfactual simulation condition), which consisted of 20 upward and 20 downward counterfactuals. No pictures were included during the simulation phase. The remaining 40 scenarios from the study phase did not re-appear during the simulation phase (No simulation condition). An equal number of items from the Identical and Counterfactual simulation conditions were presented in random order in 5 blocks of 16 scenarios, and scenarios as well as valence were counterbalanced across conditions and participants. After listening to each scenario, participants were given 7 s to imagine themselves in the already familiar scenario or in the suggested alternative scenario. In the latter case, they heard a conditional clause of the format "If A had/had not happened, then the different outcome B

could/would/might have occurred" and were instructed to imagine themselves in the scenario with outcome B. After each simulation period participants provided another valence judgment ("How did you feel when you imagined yourself in the scenario just now?") of the imagined scenario to ensure their attention to the task. They were asked to return to the laboratory approximately 48 hours later to provide more ratings of different scenarios; a 48-hour delay was used in order to avoid the possibility of ceiling effects on the final recognition test.

Recognition memory test. Following this 48-hour delay, participants were given a surprise self-paced recognition memory test of 120 scenarios consisting of 80 previously presented items and 40 items that had not appeared before. Participants made an old/new judgment for each scenario with regard to the encoding phase. They thus indicated whether they had imagined an item at encoding (old), or whether an item was completely novel or had only been imagined as an alternative but had not been presented at encoding (new). If participants decided that an item was old, they subsequently made a source judgment regarding whether the item had only been presented during the study phase (Old-No simulation), presented in both study and simulation phase (Old-Identical simulation), or presented in the study phase but imagined with an alternative outcome in the simulation phase (Old-Counterfactual simulation). If a scenario was rated as new, participants indicated whether it was completely novel (New-New) or whether it had been imagined as an alternative in the simulation phase (New-Counterfactual simulation). There was a "don't remember" option for both old and new source judgments. Participants were also asked to re-rate each scenario on the three scales described in the context of the study phase.

Half of the items on the recognition test were to be categorized as new (60), and the other half was to be categorized as old (60). Critically, 20 items (10 positive, 10 negative) represented

counterfactual lures that were to be classified as new. The remaining new items consisted of 40 (20 positive, 20 negative) never-presented, opposite-valence versions of scenarios participants had previously encountered. The old items were made up of 10 positive and 10 negative scenarios from each experimental condition. Scenarios were counterbalanced in such a way that each version of a scenario was shown equally often in each recognition test category across participants. All study materials were administered using MATLAB 7.4 on a Macbook laptop. After concluding the recognition test, participants were debriefed about the experiment.

Statistical analyses

A 2 (age: young, old) x 2 (valence: positive, negative) x 3 (condition: Identical, Counterfactual, No simulation) mixed analysis of variance (ANOVA) scheme was used to investigate differences in hit rate (number of scenarios correctly identified as old/all old items). False alarm rates (false alarms/all new items) were subjected to a 2 (age) x 2 (valence) x 2 (condition: Counterfactual simulation, Baseline) mixed ANOVA. Source identification rates were analyzed for scenarios in the Counterfactual simulation condition using a 2 (age) x 4 (condition: Old-No simulation, Old-Identical simulation, Old-Counterfactual simulation, Old-Don't know) mixed ANOVA in order to examine differences between participants' source judgments of false alarms. A 2 (age) x 3 (condition: New-New, New-Counterfactual simulation, New-Don't know) mixed ANOVA allowed us to compare participants' source identification rates for correctly identified counterfactual lures. All *post-hoc t*-tests were two-tailed and Bonferroni corrected at $\alpha = .05$. Participants' ratings of valence and past and future likelihood of occurrence were compared using Wilcoxon Signed Ranks and Mann-Whitney Tests.

Results

Ratings

Valence. The 100% response rate for behavioral ratings of emotional valence, which we collected after each trial, as well as ratings of past and future likelihood of occurrence, which participants provided after each trial in the encoding phase and the recognition memory test, confirmed that participants complied with the task. Average valence ratings did not differ between young and older participants in Experiment 1a ($U = 270.00$, $p = .71$) or Experiment 1b ($U = 238.00$, $p = .30$; see Table 4.1). Across age groups, the average emotional valence ratings for each experiment validated our categorization of scenarios as positive and negative; participants' positive and negative ratings differed significantly from each other (Expt. 1a: $Z = -4.29$, $p < .001$; Expt. 1b: $Z = -4.43$, $p < .001$). Scenarios in Experiment 1b were rated as significantly more extreme in emotional valence than those in Experiment 1a (Positive: $U = 197.00$, $p = .06$, Negative: $U = 145.00$, $p = .003$).

Likelihood. Younger and older adults deemed it not unlikely that the presented scenarios happened to them in the past or could happen to them in the future (see Table 4.1). Young adults tended to rate scenarios as more likely to occur in the future than older adults (Expt. 1a: $U = 141.00$, $p = .002$; Expt. 1b: $U = 176.00$, $p = .02$). Participants' ratings of future likelihood did not differ between experiments (Young: $U = 263.50$, $p = .61$; Older: $U = 282.50$, $p = .91$). Past likelihood ratings were not significantly different between young and older adults (Expt 1a: $U = 241.00$, $p = .33$; Expt. 1b: $U = 263.50$, $p = .61$) and experiments (Young: $U = 269.00$, $p = .70$; Older: $U = 251.00$, $p = .45$). No other differences or effects were significant or consistent across Experiment 1a and 1b.

Table 4.1

Experiment 1a/b ratings characteristics

		Young adults			*Older adults*			*Across ages*	
Measure	*Experiment*	*Positive scenarios M (SD)*	*Negative scenarios M (SD)*	*Across valence M (SD)*	*Positive scenarios M (SD)*	*Negative scenarios M (SD)*	*Across valence M (SD)*	*Positive scenarios M (SD)*	*Negative scenarios M (SD)*
Valence	1a	5.66 (0.52)	2.52 (0.55)	4.09 (0.26)	5.74 (0.49)	2.46 (0.66)	4.10 (0.39)	5.70 (0.33)	2.49 (0.41)
	1b	5.75 (0.39)	2.33 (0.92)	4.04 (0.51)	6.13 (0.47)	2.12 (0.96)	4.12 (0.43)	5.94 (0.32)	2.23 (0.71)
Past likelihood	1a	4.57 (0.84)	3.93 (0.98)	4.25 (0.82)	4.92 (0.64)	4.01 (0.83)	4.46 (0.67)	4.74 (0.58)	3.97 (0.72)
	1b	4.46 (0.79)	3.79 (0.86)	4.12 (0.74)	4.67 (0.98)	3.78 (1.15)	4.23 (1.02)	4.57 (0.60)	3.78 (0.56)
Future likelihood	1a	4.83 (0.71)	3.93 (0.95)	4.38 (0.76)	4.28 (0.99)	3.00 (0.85)	3.64 (0.86)	4.56 (0.60)	3.47 (0.62)
	1b	4.73 (0.71)	3.74 (0.88)	4.24 (0.67)	4.27 (0.96)	3.12 (1.12)	3.69 (0.97)	4.50 (0.59)	3.43 (0.60)

Note. Valence (positive/negative) refers to the first presentation of the scenario.

Memory performance

Hit rates. A 2x2x3 ANOVA of hit rates in Experiment 1a showed a significant interaction effect of age and condition, indicating that participants' hit rates in the three experimental conditions differed depending on their age group ($F(2, 92) = 3.16$, $p < .047$, $\eta_p^2 = .06$; see Table 4.2). *Post-hoc* paired *t*-tests revealed that younger adults showed a significantly higher hit rate in the Identical compared to the No simulation condition, $t(23) = 3.77$, $p < .001$, $d = 0.72$, but that hit rates in the Counterfactual simulation condition differed from neither the No simulation, $t(23) = 1.07$, $p = .30$, $d = 0.23$, nor the Identical simulation condition, $t(23) = 2.16$, $p = .04$, $d = 0.47$. Older adults, whose hit rate was lower than younger adults' across all conditions ($F(1, 46) = 4.04$, $p = .050$, $\eta_p^2 = .08$), showed a significant decline in hit rates from the Identical, to the Counterfactual, $t(23) = 3.84$, $p < .001$, $d = 0.98$, and from the Identical to the No simulation condition, $t(23) = 6.08$, $p < .001$, $d = 2.65$. The absence of a similar decline in younger adults' hit rates can likely be explained by a ceiling effect in their performance resulting in scale compression. Besides the main effects of age and condition ($F(2, 92) = 24.56$, $p < .001$;

η_p^2 = .35) underlying the interaction, no other factors had any significant effects on hit rates (all *F*s ≤ 2.25, *p* > .05).

We observed a similar pattern of results for hit rates in Experiment 1b. A 2x2x3 ANOVA resulted in a significant main effect of condition ($F(2, 92) = 38.23$, $p < .001$, $\eta_p^2 = .45$) and of age ($F(1, 46) = 11.77$, $p = .001$, $\eta_p^2 = .20$) with significantly decreasing hit rates between the Identical and the Counterfactual simulation condition, $t(23) = 3.64$, $p = .001$, $d = 0.46$, as well as between the Identical and the No simulation condition, $t(23) = 5.57$, $p < .001$, $d = .079$, in older adults, whose hit rates were lower than younger adults' across all conditions. As expected, younger adults exhibited higher hit rates in the Identical compared to the No simulation condition, $t(23) = 5.41$, $p < .001$, $d = 0.93$, but also remembered significantly more items in the Identical relative to the Counterfactual simulation condition, $t(23) = 4.34$, $p < .001$, $d = 0.74$, and in the Counterfactual relative to the No simulation condition, $t(23) = 4.05$, $p < .001$, $d = 0.60$. We also observed a main effect of valence ($F(1, 46) = 4.61$, $p = .04$, $\eta_p^2 = .09$): positive scenarios were remembered at a higher rate than negative scenarios across participants and conditions.

False alarm rates. Critically, if counterfactual simulation affects memory for the original experience, then the false alarm rates for counterfactual lures should be significantly higher compared to the false alarm rates for novel scenarios. A 2x2x2 ANOVA for Experiment 1a resulted in a significant main effect of condition on false alarm rate ($F(1, 46) = 32.21$, $p < .001$, $\eta_p^2 = .41$), with participants making more false alarms in the Counterfactual simulation condition compared to the Baseline false alarm rate to novel scenarios across both age groups (see Table 4.2 and Fig. 4.2). A significant main effect of age revealed that older adults' false alarm rate was significantly higher than younger adults' across both conditions ($F(1, 46) = 11.75$, $p = .001$, $\eta_p^2 = .20$). Our analysis also showed an age by condition interaction that approached

significance ($F(1, 46) = 3.99$, $p = .052$, $\eta_p^2 = .08$). *Post-hoc* paired *t*-tests indicated that the false alarm rate in the Counterfactual simulation condition increased more relative to the Baseline false alarm rate for older than for young adults (Older: $t(23) = 5.17$, $p < .001$, $d = 0.55$; Young: $t(23) = 2.75$, $p = .01$, $d = 0.42$). There was no effect of valence ($F(1, 46) = .33$, $p = .57$, $\eta_p^2 = .01$).

Table 4.2

Experiment 1a/b memory performance characteristics

		Expt 1a		*Expt 1b*	
Measure	*Condition*	*Young adults M (SD)*	*Older adults M (SD)*	*Young adults M (SD)*	*Older adults M (SD)*
Hit rate	Identical	0.94 (0.08)	0.92 (0.08)	0.93 (0.09)	0.80 (0.22)
	Counterfactual	0.89 (0.13)	0.83 (0.12)	0.89 (0.11)	0.69 (0.26)
	No simulation	0.86 (0.13)	0.76 (0.15)	0.82 (0.14)	0.61 (0.26)
False alarm rate	Baseline	0.09 (0.11)	0.24 (0.24)	0.06 (0.05)	0.17 (0.12)
	Counterfactual	0.15 (0.17)	0.38 (0.27)	0.24 (0.26)	0.29 (0.18)

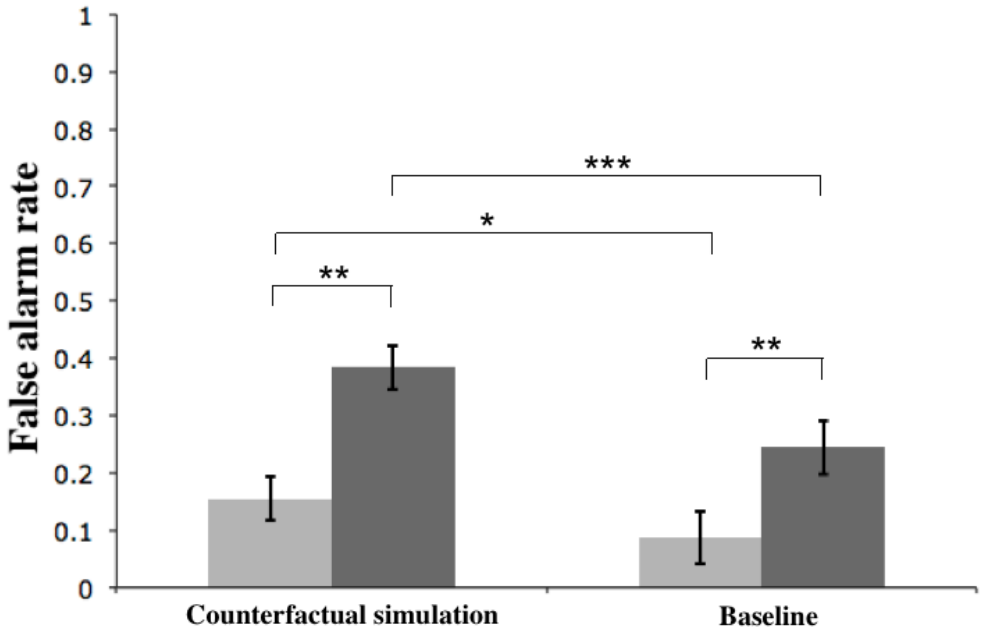

Figure 4.2. False alarm rates in response to counterfactual lures (Counterfactual simulation) and novel items (Baseline) for Experiment 1a showing a trending age by condition interaction ($F(1,46) = 3.99$, $p = .052$). Post-hoc t-tests were Bonferroni corrected, $*p < .05$, two-tailed. Error bars represent standard errors of the mean.

The corresponding 2x2x2 ANOVA for Experiment 1b replicated the significant main effect of condition ($F(1, 46) = 24.63$, $p < .001$, $\eta_p^2 = .35$) on false alarm rate (see Fig. 4.3). The main effect of age approached significance ($F(1, 46) = 3.89$, $p = .055$, $\eta_p^2 = .08$). *Post-hoc* paired *t*-tests showed that young adults had significantly higher false alarm rates in the Counterfactual simulation compared to the Baseline condition, $t(23) = 3.35$, $p = .003$, $d = 0.10$. The same pattern of results applied to older adults, $t(23) = 4.49$, $p < .001$, $d = 0.78$. Once again, valence did not affect false alarm rates ($F(1, 46) = .32$, $p = .58$, $\eta_p^2 = .01$).

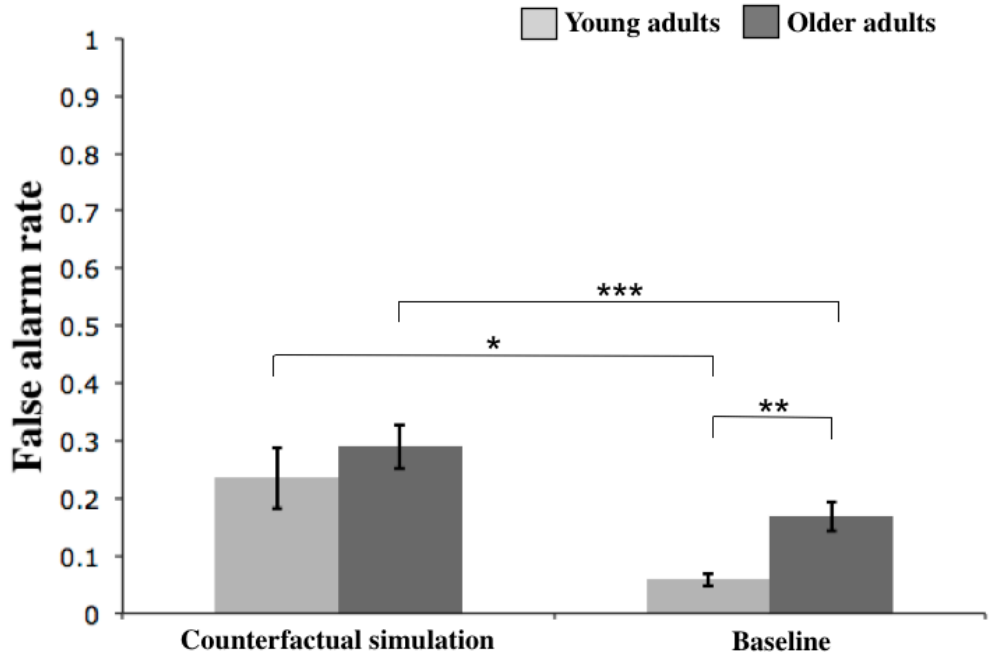

Figure 4.3. False alarm rates in response to counterfactual lures (Counterfactual simulation) and novel items (Baseline) for Experiment 1b showing a significant main effect of condition ($F(1,46) = 24.63$), $p < .001$) and a main effect of age approaching significance ($F(1,46) = 3.89$, $p = .055$). *Post-hoc t*-tests were Bonferroni corrected, *$p < .05$, two-tailed. Error bars represent standard errors of the mean.

Source identification rates. The 2x4 ANOVA of participants' source identification rates of false alarms in response to counterfactual lures in Experiment 1a yielded a significant interaction effect of age and condition ($F(3, 138) = 9.50$, $p < .001$, $\eta_p^2 = .17$; see Table 4.3). *Post-hoc* pairwise *t*-tests revealed that false alarms were most often made due to young participants identifying a counterfactual lure as a scenario they had encountered at encoding and for which they had also subsequently imagined a counterfactual outcome, instead of a scenario that was only presented at encoding, $t(23) = 2.78$, $p < .001$, $d = 1.43$, a scenario that was presented during both the encoding and the simulation phase, $t(23) = 3.72$, $p < .001$, $d = 1.60$, or a scenario whose source they did not recall, $t(23) = 2.82$, $p < .001$, $d = 1.33$. Even though older adults also displayed the highest source identification rate for the Old-Counterfactual simulation condition, it did not significantly differ from the Old-No simulation, $t(23) = 1.66$, $p = .005$ $d = 0.74$, or the Old-Identical simulation condition, $t(23) = 1.40$, $p = .06$, $d = 0.56$, though it was significantly different from the "don't know" condition, $t(23) = 3.44$, $p < .001$, $d = 1.24$.

Table 4.3

Experiment 1a/b source memory performance characteristics in response to counterfactual lures

		Expt 1a		*Expt 1b*	
Measure	*Source condition*	*Young adults M (SD)*	*Older adults M (SD)*	*Young adults M (SD)*	*Older adults M (SD)*
False alarm rate	Old-Identical simulation	0.11 (0.21)	0.27 (0.27)	0.08 (0.16)	0.34 (0.26)
	Old-Counterfactual simulation	0.60 (0.38)	0.44 (0.33)	0.71 (0.37)	0.36 (0.32)
	Old-No simulation	0.14 (0.25)	0.22 (0.26)	0.17 (0.31)	0.28 (0.33)
	Old-Don't know	0.15 (0.29)	0.06 (0.28)	0.04 (0.05)	0.01 (0.14)
Correct source identification rate	New-Counterfactual simulation	0.68 (0.33)	0.35 (0.36)	0.69 (0.27)	0.45 (0.33)
	New-New	0.26 (0.26)	0.52 (0.32)	0.25 (0.24)	0.52 (0.32)
	New-Don't know	0.06 (0.11)	0.13 (0.18)	0.03 (0.10)	0.03 (0.05)

We found an analogous pattern of results for the ANOVA in Experiment 1b, which also resulted in a significant age by condition interaction ($F(3, 138) = 7.56$, $p < .001$, $\eta_p^2 = .13$). Young adults tended to be more likely to incorrectly recall the source of a counterfactual lure to be a scenario they initially encoded and subsequently simulated counterfactually than a scenario they only encountered at encoding, $t(23) = 2.35$, $p < .001$, $d = 1.52$, a scenario they encountered in the same form during the encoding and the simulation phase, $t(23) = 2.84$, $p < .001$, $d = 2.21$, or a scenario of which they lacked source knowledge, $t(23) = 3.03$, $p < .001$, $d = 2.54$. Older adults' source identification rates were much more evenly spread out between the Old-Counterfactual simulation and the Old-Identical simulation condition, $t(23) = .84$, p = .71. $d =$ 0.07, as well as the Old-Counterfactual and the Old-No simulation condition, $t(23)= 1.13$, p = .50, $d = 0.25$, though the counterfactual rates were significantly different from the "don't know" option, $t(23) = 4.25$, $p < .001$, $d = 1.42$.

Counterfactual lures that were correctly identified as new in Experiment 1a showed a significant age by condition interaction for their source identification rates ($F(2, 92) = 9.44$, $p < .001$, $\eta_p^2 = .17$). *Post-hoc t*-tests revealed that young participants were able to correctly identify the source of most counterfactual lures instead of categorizing them as completely novel scenarios, $t(23) = 3.52$, $p = .002$, $d = 1.41$, or indicating their lack of source memory, $t(23) = 7.27$, $p < .001$, $d = 0.48$. In contrast, older adults' source identification rates did not differ significantly between their categorization of counterfactual lures as completely novel and as having been imagined as an alternative, $t(23) = 1.24$, $p = .23$ $d = 0.50$, and between the latter and the "don't know" option, $t(23) = 2.41$, $p = .03$, $d = 0.77$.

Experiment 1b replicated the significant interaction effect of condition and age for correctly identified counterfactual lures ($F(2, 92) = 8.47$, $p < .001$, $\eta_p^2 = .16$). Young adults in

this experiment were also significantly more likely to remember the correct source of a counterfactual lure instead of classifying a it as novel scenario, $t(23) = 4.50$, $p < .001$, $d = 1.72$, or admitting to not remembering the source, $t(23) = 9.31$, $p < .001$, $d = 3.24$. Again, older adults' source identification rates did not differ between the correct New-Counterfactual simulation and the New-New condition, $t(23) = 0.49$, $p = .63$, $d = 0.22$.

Discussion

Experiments 1a and 1b both revealed that participants made false alarms in response to counterfactual lures above and beyond novel items, indicating that counterfactual simulation distorted their memory of the original event, and that the effect applies both to everyday scenarios of relatively low and high emotional valence. The distorting effect of counterfactual simulations was more pronounced in older adults, confirming previous findings of older adults' increased susceptibility to memory distortions in related paradigms (e.g., Hashtroudi et al., 1990; Jacoby et al., 2005; McDaniel et al., 2008; Remy et al., 2008; Roediger & Geraci, 2007; Schacter et al., 1997). False alarms were most often due to participants identifying a counterfactual lure as having been encountered at encoding, thereby making a source attribution error and confusing the memory of the counterfactual simulation with the memory of the original event. Unlike younger adults, older adults were close to chance with their source judgments between the three experimental conditions. When participants correctly identified counterfactual lures as new, only young adults were able to make correct source judgments about them. Older adults, in turn, classified approximately half of the counterfactual lures as entirely novel scenarios, indicating that they had forgotten the previous counterfactual simulation, which may have protected them from making even more false alarms.

Valence did not seem to play a role in counterfactual memory distortions, even for older adults. One possibility is that upward and downward counterfactual lures do not differentially affect memory for a scenario. In addition, the positivity effect previously observed in older adults may not apply in this context. Alternatively, it could be that upward and downward counterfactuals need to be simulated for actual experiences, as opposed to the hypothetical scenarios we used, in order to show any difference. To test whether the findings of Experiments 1a and 1b extend to performed actions and whether we could replicate our results with very different materials, Experiment 2 examined the effects of counterfactual simulations on actions performed in the laboratory.

Experiment 2

In Experiment 2, participants were asked to perform actions and were rewarded for half of them in order to create positive and negative experiences. These experiences set the stage for upward counterfactual simulations of the action a participant should have performed instead in order to obtain the reward, and downward counterfactual simulations of the action a participant would have performed had they not selected the rewarded action. The reward system used in the experiment was based on a cover story, according to which participants were supposed to choose and perform the action of a pair of actions that had been shown to be the more popular of the two in previous experiments. The remaining overall design of this experiment was similar to that of Experiments 1a/b, in that the performed actions were recalled, simulated counterfactually, or not at all presented during a simulation phase, which followed an encoding phase and preceded a delayed old/new recognition memory test. The critical questions were whether counterfactual lures would again elicit false alarms in our participant groups, would do so to a greater extent in

older adults, and whether any differences between upward and downward counterfactuals would emerge using our task involving performed actions.

Method

Participants

24 young adults (13 female; M_{age} = 22 years, SD_{age} = 2.5) between 18 and 29 years of age and 24 older adults (13 female; M_{age}= 75 years, SD_{age} = 8.2) between 60 and 93 years old gave informed consent to participate in this experiment according to the same criteria as in Experiment 1.

Materials

The stimuli for Experiment 2 comprised 50 pairs of actions adapted from McDaniel et al. (2008), such as chaining paper clips in a line (action A) or a circle (action B) or clapping one's hands together (action A) or snapping one's fingers (action B; see Supplementary Table 4.1). 25 action pairs involved objects; the remaining 25 required physical gestures.

Design and Procedure

The main design consisted of a 2 (age) x 2 (valence) x 3 (condition) mixed factorial with valence and condition as within-subject factors and age as the between-subject factor.

Encoding phase. Experiment 2 was structured very similarly to Experiments 1a/b: Participants engaged in a two-phase study period divided by a 10min distractor task and completed a surprise recognition memory test one week after the encoding and simulation phases. During the encoding phase, participants were presented with 40 pairs of actions and were asked to choose the action of each pair that they considered the more popular choice. As the cover story for the reward system in this experiment, participants were told that a previous study had identified the action of each action pair that most people preferred to perform, and that their task

was to correctly choose said action in order to receive a 10-cent reward. Each trial was pre-determined to result in a 10-cent reward or no reward, which was counterbalanced across participants, with 50% of trials yielding a reward. After choosing an action, participants were informed whether or not they received a reward for their choice and subsequently performed the chosen action.

Simulation phase. Following a 10-min unrelated distractor task (beginners' Sudoku), participants were asked to imagine 30 actions in three distinct ways. They recalled performing 10 actions (5 rewarded, 5 unrewarded) from the encoding phase (Recall condition), they imagined performing the rewarded, previously *not* chosen action of 10 action pairs (Upward counterfactual simulation condition), and they imagined performing the unrewarded, previously *not* chosen action of another 10 action pairs (Downward counterfactual simulation condition). These simulations were administered in random order and were repeated three times for each action. 10 out of the 40 action pairs from the encoding phase were not presented in any way during this study phase (No simulation condition). All actions were counterbalanced in such a way that each action was shown equally often in each condition across participants.

Recognition memory test. One week later, participants completed a paper-and-pencil surprise recognition memory test. Of the 100 actions on the test, participants had viewed 80 during the encoding phase (and chosen 40), and 20 actions were completely novel. They were to indicate that an action was *old* if they had performed it during the encoding phase, and that an action was *new* if they had not performed it during the encoding phase (i.e., it was completely novel or represented an alternative action they had not been chosen in the encoding phase). All participants were debriefed about the experiment.

Statistical analyses

In order to examine differences in hit rates as well as false alarm rates, we conducted 2 (age) x 2 (valence) x 3 (condition) mixed ANOVAs with valence and condition as within-subject factors and age as the between-subject factor. All *post-hoc t*-tests were two-tailed and Bonferroni corrected at $\alpha = .05$.

Results

Memory performance

Hit rates. A 2x2x3 ANOVA of hit rates resulted in a significant interaction of age by valence by condition ($F(2, 92) = 4.75$, $p = .01$, $\eta_p^2 = .09$), with older adults producing significantly lower hit rates across conditions and valence compared to younger adults ($F(1, 46) = 8.98$, $p = .004$; $\eta_p^2 = 0.16$; see Table 4.4). *Post-hoc* paired *t*-tests showed that older adults correctly remembered more rewarded tasks from the Recall condition than the No simulation condition, $t(23) = 4.52$, $p < .001$, $d = 1.05$, as well as more rewarded tasks from the Downward counterfactual simulation than the No simulation condition, $t(23) = 3.86$, $p < .001$, $d = 1.03$.

Table 4.4

Experiment 2 memory performance characteristics

Measure	*Condition*	*Valence*	*Young adults M (SD)*	*Older adults M (SD)*
Hit rate	Identical	Rewarded	0.85 (0.18)	0.81 (0.18)
		Unrewarded	0.86 (0.19)	0.69 (0.29)
	Counterfactual	Downward	0.80 (0.18)	0.77 (0.09)
		Upward	0.80 (0.17)	0.66 (0.18)
	No simulation	Rewarded	0.79 (0.22)	0.61 (0.20)
		Unrewarded	0.66 (0.23)	0.58 (0.28)
False alarm rate	Counterfactual		0.22 (0.16)	0.45 (0.20)
	Control		0.13 (0.09)	0.33 (0.21)
	Recall		0.13 (0.12)	0.36 (0.29)
	No simulation		0.13 (0.10)	0.31 (0.19)
	Novel		0.02 (0.03)	0.10 (0.13)

Note. False alarm rates for the Recall and No simulation condition were combined in the Control condition.

False alarm rates. Importantly, participants made false alarms to 1) items that had been viewed but not selected during the encoding phase of the Recall condition, 2) items that had been viewed but not selected during the encoding phase of the No simulation condition, 3) items that had been simulated as counterfactuals, and 4) items that were completely novel. A 2x2x3 ANOVA of false alarm rates in conditions 1) through 3), which included rewarded and unrewarded trials at encoding, yielded no significant age by valence by condition interaction, valence by condition interaction, or main effects of valence (all Fs ≤ 1.23, $p \geq .29$). We further determined that there was no difference between false alarm rates in response to previously non-selected items in the Recall and No simulation conditions in either age group (Young: $t(23) = 0.18$, $p = .86$, d = 0.09; Older: $t(23) = 1.15$, $p = .26$, $d = 0.20$) and thus combined the false alarm rates from both conditions to form a Control condition. A 2x3 ANOVA comparing false alarm rates in the Counterfactual simulation, Control, and Novel conditions yielded a significant age by condition interaction ($F(2, 92) = 5.94$ $p = .004$, $\eta_p^2 = .11$; see Table 4.4 and Fig. 4.4). *Post-hoc* independent *t*-tests indicated that the extent to which older adults made more false alarms than younger adults was higher in the Counterfactual simulation and Control condition than in the Novel condition (Counterfactual: $t(46) = 4.51$, $p < .001$, $d = 1.27$; Control: $t(46) = 4.30$, $p < .001$, $d = 1.20$; Novel: $t(46) = 3.10$, $p = .003$, $d = 0.85$). There was also a significant counterfactual simulation effect in young adults, who produced more false alarms in response to Counterfactual simulations than items in the Control, $t(23) = 3.16$, $p = .004$, $d = 0.69$, or Novel condition $t(23) = 6.42$, $p < .001$, $d = 1.74$.

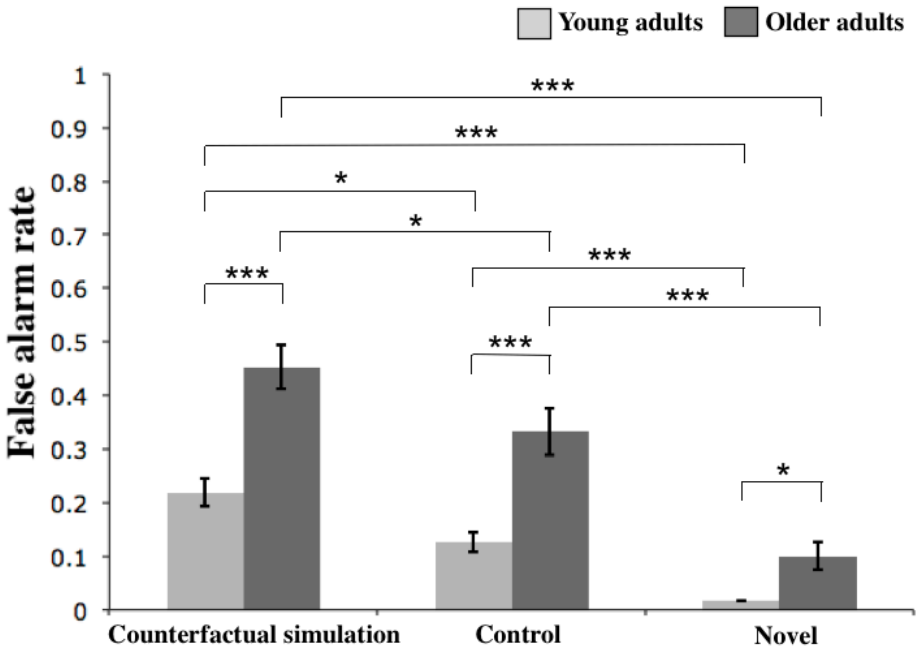

Figure 4.4. False alarm rate in response to counterfactual lures (Counterfactual simulation), actions that were viewed but nor performed at encoding (Control), and novel items (Novel) for Experiment 2 showing a significant age by condition interaction ($F(2,45) = 4.98$, $p < .05$). *Post-hoc t*-tests were Bonferroni corrected, *$p < .05$, two-tailed. Error bars represent standard errors of the mean.

Discussion

Experiment 2, which was based on performing real actions at encoding, yielded even more pronounced effects of counterfactual thinking on memory than did Experiments 1a and 1b. Older adults made false alarms in response to counterfactual lures to a greater extent than younger adults, producing a false alarm rate that exceeded those in Experiments 1a and 1b. Critically, both age groups' false alarm rates in response to counterfactual lures were not only significantly higher relative to their false alarm rates in response to entirely novel actions, but also surpassed false alarm rates in response to lures of actions that had been viewed and considered, but had not been chosen and performed at encoding. This finding serves to emphasize the role of *simulation* – as opposed to mere exposure to an alternative – in the

memory distortion observed here. Analogous to Experiments 1a/b, participants had similarly high false alarm rates in response to counterfactual lures whether their counterfactual simulation had been upward or downward. Experiment 2 also replicated the general pattern of hit rates found in the previous experiments, which declined slightly between the Recall, Counterfactual, and No simulation conditions.

Summary and Concluding Discussion

Our experiments revealed, for the first time, that episodic counterfactual thinking can affect memory for past events, and can do so to a greater extent in older than in young adults. Even though people frequently engage in counterfactual thinking in everyday life, and even though it has been investigated in the context of a number of other cognitive domains, no prior research had examined whether simulating an alternative past event could affect a person's memory of the original event. Experiment 1a used everyday scenarios in which participants could envision themselves in order to create experiences to which they subsequently imagined alternative outcomes. In a recognition memory test participants falsely recognized counterfactual scenarios as originally presented scenarios and also did so when we used scenarios of more extreme valence in Experiment 1b. Experiment 2 replicated Experiment 1a and 1b's findings of counterfactual simulation effects on memory using very different materials and asking participants to perform actions in the laboratory.

These findings are consistent with our hypothesis that episodic counterfactual simulations can serve as a form of internally generated misinformation (Loftus, 2005). While previous research on misinformation has shown memory distortions after introducing external misinformation, counterfactual simulations in real life are triggered automatically and internally. In response to an experience, we can fabricate counterfactual misinformation ourselves by

constructing and envisioning an alternative to the original experience. Related research has already shown that the act of simulation can elicit memory confusion, which can cause a person to falsely recollect imagined novel events as real memories (e.g., Garry et al., 1996; Loftus, 2003; Mazzoni & Memon, 2003). However, it was previously unclear whether episodic counterfactual simulations could have effects on memory similar to misinformation or imagination inflation, as counterfactual simulations are by definition tied to the factual past event. The way in which counterfactuals are typically imagined directly highlights the discrepancy between the actual and the counterfactual outcome: If outcome A had not occurred, outcome B could have occurred instead. This contrasting link between the original outcome and the counterfactual outcome could have decreased participants' vulnerability to memory errors and instead strengthened memory accuracy for the original event.

In the current paradigms we asked participants to engage in vivid simulations of alternative scenarios or actions, which seems to in some cases have rendered the alternative simulation as memorable as the original event. Our source attribution findings from Experiment 1a/b confirmed that participants tended to misremember the source of their recognition memory when making false alarms. We therefore suggest that episodic counterfactual simulations can act as a kind of internally generated misinformation that can cause source confusion, in line with findings and ideas from previous research reported in the classic misinformation paradigm (e.g., Higham, Luna, & Bloomfield, 2011; Lindsay, 1990; Loftus, 2005; Zaragoza & Lane, 1994). While the misinformation in our experiments was internally generated, we did provide participants with the contents of their counterfactual simulations. Spontaneously self-generated and possibly repeated episodic counterfactual simulations in real life may be even more powerful

at rendering the alternative simulation as memorable as or possibly more memorable than the original event.

Even though people typically produce upward counterfactuals more often than downward counterfactuals (Summerville & Roese, 2008), and even though, as we discussed in the introduction, upward and downward counterfactuals have differential effects on emotion regulation and goal-directed behavior (Epstude & Roese, 2008), our findings provide no evidence that valence plays a role in the effect of episodic counterfactual simulations on memory in younger or older adults. Although, as noted earlier, older adults often exhibit a positivity bias (Mather & Carstensen, 2005), which led us to suggest that they might be especially prone to distorting effects of downward counterfactuals, the positivity bias is not observed across all tasks and situations (e.g., Gruhn, Smith, & Baltes 2005; Kensinger, Garoff-Eaton, & Schacter, 2007; Kensinger & Schacter, 2008). Thus one possibility is that an age-related positivity bias does not extend to the domain of counterfactual simulation. Another possibility is that the constructs of upward and downward counterfactuals do not map in any simple or direct way onto to the constructs of negative and positive information as studied in the cognitive aging literature. Finally, it is possible that differential effects of upward and downward counterfactuals might only be observed for real-life experiences that are highly meaningful to participants. Future research that explores whether counterfactual simulations can affect everyday autobiographical memory would be well positioned to determine whether a distinction between the effects of upward and downward counterfactuals can be observed in either young or older adults.

Our experiments represent only a beginning attempt to examine the effects of episodic counterfactual simulation on memory and to contribute to the discussion of counterfactual thinking as a specific type of adaptive constructive process. The role of counterfactual

simulations in creating memory confusion fits with the general notion discussed earlier that some adaptive processes that enhance the efficient operation of memory and cognition also create distortions as a result of doing so (e.g., Bartlett, 1932; Brainerd & Reyna, 2005; Howe, 2011; Johnson & Sherman, 1990; Newman & Lindsay, 2009; Roediger, 1996; Schacter, 2012; Schacter & Addis, 2007; Schacter et al., 2011). However, based on the lack of valence effects in the current results, there does not seem to be a direct relationship between the proposed functionality of counterfactuals and the likelihood of counterfactuals to create memory confusion. If upward counterfactuals prepare a person for similar future scenarios, being more likely to remember the more successful way of action as part of the upward counterfactual would be more adaptive than remembering a downward counterfactual outcome, which would stand in the way of emotion regulation. Further research should examine whether upward and downward counterfactuals in response to meaningful real-life events show a differential likelihood to cause memory confusion.

Real-life counterfactual thinking in response to very salient past events may occur repeatedly, which could decrease the likelihood of memory confusion and render counterfactual simulations more functional, as long as they are not repeated excessively. There was no difference in the extent to which participants' memory was distorted between Experiment 1, which required one counterfactual simulation per trial, and Experiment 2, which required three repeated simulations (but also contained very different materials than Experiment 1). However, recent research on the effects of repeated imagining on the perceived plausibility of episodic counterfactual simulations has found that perceived plausibility decreases with repeated simulations across upward and downward counterfactuals (De Brigard, Szpunar, et al., in press). This finding could have implications for understanding memory for episodic counterfactual simulations that should be investigated: While repeated counterfactual simulations should render

counterfactuals more memorable, decreased perceived plausibility may counteract any memory confusion.

Finally, the effect of counterfactual simulations on memory should also be considered in light of less common responses to counterfactual simulations (Markman & McMullen, 2005): Instead of generating a sense of relief, simulating downward counterfactuals can sometimes trigger feelings of fear or guilt. Upward counterfactuals, in turn, can bring about positive feelings ("I almost won the race and am likely to win next time") instead of regret or disappointment. Taking into account these finer distinctions between affective responses to counterfactual simulations, as well as other features of everyday counterfactual simulations, such as perceived plausibility and meaningfulness, should increase our understanding of how and when counterfactual thinking helps coordinate cognitive processes such as memory, and how, when, and why it may result in error or illusion.

General Discussion

The three dissertation papers examined different types of goal-directed simulations: problem-solving, process, outcome, and counterfactual simulations. Papers 1 and 2 investigated the neural correlates of goal-directed simulations and revealed that these episodic simulations did not only engage regions of the default network - contrary to its previous categorization as a "task-negative" network -, but that default network regions also formed functional networks with other brain regions, such as executive dorsolateral prefrontal cortex. Additional evidence of the default network's ability to be coactive with the frontoparietal control network has recently been accumulated in studies of scene construction (Summerfield, Hassabis, & Maguire, 2010), autobiographical planning (Spreng et al., 2010; Spreng & Schacter, 2012), mind-wandering (Christoff et al., 2009), evaluation of one's creative ideas (Ellamil, Dobson, Beeman, & Christoff, 2012), movie watching (Gao & Lin, 2012), and social working memory (Meyer, Spunt, Berkman, Taylor, & Lieberman, 2012). In one such study, Spreng et al. (2010) asked participants to construct personal plans based on several given steps and obstacles to be overcome in order to meet specific life goals, such as "freedom from debt". Throughout this goal-directed simulation task, default network activity was coupled with the frontoparietal control network. Similarly, default network regions in the medial temporal lobe joined forces with executive dorsolateral prefrontal cortex when participants evaluated creative drawings and writings they had generated in the scanner (Ellamil et al., 2012). Further converging evidence was contributed by a study on social working memory, where default and frontoparietal network regions were engaged during a social cognition task, and frontoparietal network activity increased with information load (Meyer et al., 2012). During a scene construction task supported by the default network, participants had to integrate varying numbers of sequentially presented elements into an imaginary scene. Here,

executive prefrontal cortex activity increased with the number of elements to be incorporated (Summerfield et al., 2010). In another recent study, Gao and Lin (2012) asked participants to watch a nature movie while in the scanner and found that default and frontoparietal control network activity was correlated throughout the task.

Taken together, these reports present significant evidence of the interactivity of the default and frontoparietal networks during certain internally-focused cognitive tasks, rendering the initial notion of a consistently task-negative default network obsolete (e.g., Spreng, 2012). The findings in Papers 1 and 2 are also in line with a recently proposed mechanism for the networks' interactivity, whereby the frontoparietal network is hypothesized to sustain internal trains of thought and support default network activity by shielding it from distractions of exogenous stimuli, by directing a train of thought toward a goal, and by helping integrate information (Gao & Lin, 20012; Smallwood et al., 2012; Spreng et al., 2010). However, there is also some evidence that the frontoparietal control network may not always act as a unitary network and may be dissociable into *salience processing* regions, including dorsal anterior cingulate, orbital frontoinsular cortices, and subcortical/limbic structures, and *executive control* regions, including dorsolateral frontal and parietal cortex regions (Seely et al., 2007). Results from the present papers do not seem to follow this dissociation, though the problem-solving and process simulations appear to recruit more executive control regions, such as dorsolateral prefrontal cortex and anterior inferior parietal lobule than salience processing regions. The default network has also been found to consist of dissociable subsystems that facilitate distinct cognitive processes (Andrews-Hanna, Reidler, Sepulcre, et al., 2010): Posterior and anterior medial prefrontal cortex are thought to support self-referential and affective decision-making, whereas medial temporal lobe regions are more engaged during mental scene construction and

recall. The involvement of both of these subsystems in the present goal-directed simulations is a reflection of the complex nature of these simulations, which require individuals to generate different steps and scenes, imagine themselves in those scenes, and make decisions about information to integrate into a coherent sequence.

Paper 2 also revealed that the default network's ability to be coactive with other brain networks or components thereof during goal-directed simulations is not restricted to the frontoparietal control network. During outcome simulations, regions of the default network formed a functional network with a set of regions that has been implicated in reward-processing (e.g., Liu et al., 2011). We hypothesized that the recruitment of the reward-processing regions aided default network regions in assessing the affective impact of the generated simulations and in allowing participants to pre-experience the potential reward of achieving a goal. This finding contributes further to the evidence that the default network can dynamically interact with different brain networks according to the demands of certain internally focused and self-projective tasks that can be goal-directed. Given that a growing body of research is identifying the brain's organization into complex and dynamically interacting networks (Yeo et al., 2011; Laird et al., 2009), it is critical to improve our understanding of how, when, and why different networks are coactive or dissociable.

Implications for behavior

The findings from Papers 1 and 2 also have several implications for goal-directed behavior. For one, they highlight the different characteristics of problem-solving, process, and outcome simulations and the ways in which these simulations could be utilized most effectively. Our results confirm that executive processes are at the core of planning simulations, such as problem-solving and process simulations, which converge with the previous neuropsychological

and non-episodic literature on planning (e.g., Eslinger & Damasio, 1985; Luria, 1996; Shallice, 1982). Unlike previous studies of process and outcome simulations that were focused on one goal (Chan & Cameron, 2012; Pham & Taylor, 1999; Taylor & Pham, 1996, Taylor et al., 1998), participants in Paper 2 were asked to produce episodic simulations and subsequently provide ratings for almost 100 goals. These ratings allowed us to reveal possible differential effects of the two types of simulations on variables that might mediate subsequent goal achievement, such as the level of motivation to attain a goal or the subjective desirability of a goal. Taylor and colleagues (1998) hypothesized that their participants performed better after rehearsing process simulations because they felt that the desired goal was less difficult to achieve and experienced reduced levels of anxiety. However, the present participants' behavioral ratings did not confirm this link between process simulations and reduced levels of subjective difficulty and anxiety: Participants rated process goals to be as difficult to achieve as outcome goals and were similarly confident in the goals' achievability. Our results suggest that people are quite adept at formulating hypothetical plans to achieve future goals but do not confirm previously suggested mechanisms linking process simulations to goal attainment.

Participants found outcome simulations to be as detailed and easy to produce as process simulations, providing further evidence for the equivalence and adaptiveness of both types of goal-directed simulations. The neuroimaging results of Paper 2 confirmed the affective impact of outcome solutions, which recruited default network and reward-processing regions that have previously been implicated in imagining positive rather than negative events (Sharot et al., 2007; D'Argembeau et al., 2008), simulating consequences of receiving a reward (Benoit et al., 2011; Peters & Büchel, 2010a), and anticipating or evaluating possible rewards (Liu et al., 2011). Participants rated goals whose achievement they had simulated as more desirable and important,

and were biased to make such goals their own. Even though participants pre-experienced the joy of achieving a goal during outcome simulations, they were not more motivated to attain the goal than if they had undergone process simulations. Taylor and colleagues (1998), as well as Oettingen (1996) have proposed that the anticipatory consummation of success may keep individuals from initiating goal-directed actions, which are likely to be less enjoyable than daydreams of achievement. In Taylor and colleagues' (1998) experiment, the affective benefits of outcome simulations seemed to interfere with their participants' goal of doing well on an exam when they failed to study more, eventually reduced their aspirations, and produced poorer grades than those who had rehearsed process simulations. However, a recent study by Chan and Cameron (2012) revealed that outcome simulations had a more positive effect than process simulation on their participants' goal of increased fitness. Their inactive participants' motivation to exercise and the amount of physical activity in which they subsequently engaged increased significantly following outcome simulations of being stronger, happier, and more energetic relative to process simulations of imagining returning home after work, changing into sports clothes, and driving to the beach to go for a walk. Future research needs to examine whether the effect of process and outcome simulations differs depending on the type of goal to be achieved, and what kinds of mechanisms can reliably bring about adaptive effects of either type of simulation on goal achievement. Our neuroimaging findings provide the basis for exploring such mechanisms not only on a behavioral, but also on a neural level, allowing further studies to identify brain regions that moderate behavioral effects, such as the subsequent recall or enactment of goals.

Counterfactual simulations of the past have already been shown to have positive effects on future behavior (e.g., Ciarocco et al., 2010; Markma et al., 2008; Smallman & Roese, 2009)

but have been studied less as a constructive process that can also be maladaptive. Paper 3 of this dissertation revealed such a potential downside of counterfactual simulations of past events. Its results suggest that both upward and downward episodic counterfactual simulations of past events can function as a type of internally generated misinformation. Especially older adults were prone to misremembering counterfactual simulations as the original past event. However, it has yet to be determined whether this effect carries over to salient autobiographical memories, and to what extent repetition, emotional valence, and perceived plausibility of counterfactual simulations might affect memory for past experiences that triggered counterfactual thinking. Even though this kind of source confusion appears to be maladaptive, one could also take the perspective that, in the case of the more common upward counterfactual simulations, it is more important to remember the lesson from a past failure than to be able to recall the original event in order to adjust one's future behavior.

Implications for errors of prediction

There are many other contexts in which process and outcome simulations may have adaptive value that have yet to be explored. When thinking about future goals, we often delay intentions, procrastinate on achieving our goals, and suffer from the planning fallacy when we vastly underestimate how long it will take us to complete a task (e.g., Buehler et al., 1994; Buehler, Griffin, & Peetz, 2010). Drawing on process and outcome simulations may help ameliorate common pitfalls of future simulations and predictions (Dunning, 2007; Gilbert & Wilson, 2007). Gilbert and Wilson (2007) have recognized several errors of prediction stemming from episodic future simulations, three of which might be alleviated by employing the right kind of goal-directed future simulation. The first of these errors is based on our tendency to imagine only the defining features of an event, leaving out inessential, yet important details of future

events, such as the process necessary to achieve a desired goal, especially when we imagine a distant future episode. When imagining proximal goals, Christian, Miles, Fung, Best, and Macrae (2013) recently found that participants concentrated mostly on task-relevant characteristics of future goals, such as the size of a pyramid when they imagined traveling to Egypt to climb a pyramid. In contrast, another group of participants that were asked to imagine traveling to Egypt to take a picture of a pyramid focused on the compositional complexity of the scene instead. By taking advantage of characteristics of process simulations that allow us to generate a number of plausible steps, put them into a coherent sequence, and project ourselves going through these steps in the future, process simulations should help capture some of the less essential features of future events that we might otherwise neglect: For instance, if we have a tendency to only imagine how enjoyable it would be to meet up with a friend over dinner in a few weeks and do not think about the fact that we will have to take public transportation to travel across town in likely miserable January weather to do so, detailed process simulations of how we would reach the desired goal would allow us to make a better decision about when and where to have dinner, avoiding an otherwise likely cancellation or unhappy journey. A second frequent error of prediction involves the abbreviated nature of many episodic future simulations – we tend to focus on the first few moments of a hypothetical future event and fail to think about how the remainder might impact us. In keeping with our example, a more extensive outcome simulation of the dinner with our friend that capitalizes on the demonstrated affective pre-experience of the future event might help us remember that, while we generally really enjoy the first half hour of conversation, we also tend to grow quite tired of our friend's argumentative tendencies. A more detailed outcome simulation might lead us to make the decision to invite another friend along for dinner to diffuse the situation.

Process simulations are also well set up to alleviate the common error of decontextualization: We often fail to take into account that we are likely to find ourselves in different circumstances during the future event than our present context – for instance, we may currently be relaxed and happy but might be stressed and hungry at the time of the future event, which is likely to impact our emotional responses and decisions. However, if we engaged in a more detailed process simulation of the potential future context, which in the case of our example could include our departure from work on our way to dinner, we might realize that we would be going through a particularly stressful period at work during the week of the dinner and would be unlikely to be able to leave in time. A combination of detailed process and outcome simulations should thus help us avoid common pitfalls of prediction, so that we would be less likely to cancel dinner with our friend and would instead schedule it during a less stressful week when another friend would be available to join us.

Other frequent prediction errors occur due to 1) the planning fallacy, our tendency to misjudge how long it will take to complete a task, and 2) our inclination to neglect alternative future outcomes (Dunning, 2007). Engaging in episodic counterfactual simulations could be beneficial in both cases: For instance, studies have shown that taxpayers consistently underestimate how long it will take them to file their return (Buehler et al., 1994; Buehler, Griffin, & McDonald, 1997). If planning for a reoccurring goal such as filing income taxes, taking advantage of memorable counterfactual simulations of how we could have avoided having to stay up all night on April 14 by starting to work on our taxes a week early should lead us to avoid a similar planning fallacy in the future. Engaging in counterfactual simulations of alternative *future* outcomes, also termed *prefactual* thinking (e.g., Epstude & Roese, 2011), would help alleviate our propensity to focus on a specific outcome, which may account for why

people are often overconfident and overoptimistic in their predictions (Dunning, 2007). In one study that demonstrated our tendency to be overconfident, Koriat, Lichtenstein, and Fischhoff (1980) showed that college students who answered trivia questions and were asked to provide possible reasons for why their answers might be correct or incorrect, were much more prone to simulating reasons that supported their answers and reflected how confident they felt in their correctness than reasons for why they might be wrong. Similarly, people tend to generate overly optimistic future scenarios rather than more negative alternatives. Participants that were asked to generate task completion plans were significantly more likely to decide on overly optimistic than realistic completion deadlines (Newby-Clark, Ross, Buehler, Koehler, & Griffin, 2000). If individuals were lead to generate more elaborate prefactual outcome simulations or simulated several possible outcomes for a person other than themselves, which appears to decrease maladaptive predictive bias in the case of task completion times (Newby-Clark et al., 2000), these effects could be diminished. These possible uses of goal-directed simulations suggest that understanding more about the features of such episodic simulations could not only have beneficial effects on behavior but also improve our often-flawed future predictions.

Outstanding questions and issues

The three papers of this dissertation contribute to our understanding of the cognitive neuroscience and adaptiveness of goal-directed simulations, but there is much left to be examined. Many of the phenomenological characteristics of goal-directed simulations have yet to be investigated in order to obtain a more complete picture of how frequently we engage in which types of simulations (including, for example, prefactual simulations), how often they tend to be combined and repeated, and to what extent and under what circumstances their components, such as mental imagery, executive, semantic, and affective processes, vary. Such analyses will also

help us learn more about the nature of mind-wandering, which has been equated with unstructured fantasizing, cognitive failure, and distraction. However, recent studies have revealed that individuals tend to engage in goal-directed simulations during mind-wandering (Baird et al., 2011; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011). This evidence stands in contrast with the finding that people report to be unhappy during mind-wandering (Killingsworth & Gilbert, 2011), since planning for upcoming goals (e.g., Emmons, 1996; Freund & Baltes, 2002; Klinger, 1977; Wiese, 2007) and generating desired outcomes have also been associated with reward (see Paper 2). Further research will have to elucidate the relationship between the contents and circumstances of mind-wandering and perceived happiness.

A main aim of the research on goal-directed simulations should be to establish a tighter link between simulations and behavior in order to better equip individuals to reach the future they envision. Even though there is some evidence for an effect of process simulations driving goal-directed behavior and improving goal performance (Taylor et al., 1998), it is inconsistent with some of the current behavioral findings and needs to be tested in a variety of contexts beyond academic performance. We now have a basis for beginning to unravel the neural mechanisms that modulate different components of simulations and lead certain simulations to be remembered and enacted. We will also be able to determine when and how goal-directed simulations might turn from a helpful simulation to a harmful rumination, which would benefit various clinical populations. Once such links between goal-directed simulations and behavior have been established more reliably, episodic simulations could become a powerful tool to help individuals reduce common planning and prediction mistakes. Goal-directed simulations could potentially be used as an intervention to improve the well-being of specific populations, such as older adults, whose happiness may be increased by encouraging them to set, simulate, and enact

personal goals directed at self-development and their own and others' well-being (Lapierre et al., 1997). Depressed or anxious populations may benefit from using certain types of goal-directed simulations to decrease a fear of failure or tendency to ruminate (e.g., Flett, Madorosky, Hewitt, & Heisel, 2002; Jones, Papadakis, Hogan, & Strauman, 2009; Nolen-Hoeksema, 2000). Basic findings of this ability of mental simulations already exist but need to be expanded to episodic, goal-directed simulations, which are so prevalent in our everyday lives.

Conclusion

This dissertation has examined neural and behavioral aspects of goal-directed simulations of past and future events and laid the groundwork for further research on the neural and behavioral mechanisms underlying these essential simulations. The first two papers demonstrated the adaptive ability of the default network to couple with frontoparietal network as well as reward-processing regions during goal-directed simulations, providing evidence that the default network can support not only internally focused and self-referential, but also goal-directed cognition, and can flexibly interact with other networks. Behavioral assessments of a large number of simulated goals allowed us to measure the perceived impact of goal-directed simulations on goals, and we discussed possible implications for further studies examining links between simulations and behavior. The third paper focused on more maladaptive functions of goal-directed simulations, showing that counterfactual simulations of past events can lead to source confusions between the simulation and the original event. This collection of papers serves as a starting point for further investigation of everyday goal-directed simulations as adaptive, constructive processes with various potential benefits as well as downsides.

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Appendix

Supplemental Table 2.1

Peak regions of activation for problem-solving simulation > fixation

		MNI coordinates			
Lat	**Region**	**x**	**y**	**z**	**t**
B	MSFG	-6	22	39	9.84
L	IFG	-45	16	24	9.33
R	PC	45	-62	-33	9.08
L	DLPFC	-36	4	48	8.99
L	PC	-33	-53	-27	7.66
R	OP	15	-95	0	7.53
L	SPL	-39	-35	45	7.30
L	OP	-15	-95	0	7.29

Supplemental Table 2.2

Peak regions of activation for semantic association > fixation

		MNI coordinates			
Lat	**Region**	**x**	**y**	**z**	**t**
B	MSFG	-3	22	39	12.83
L	LG	-12	-95	-3	11.93
L	alfO	-30	22	0	10.95
R	PC	45	-56	-33	10.80
R	alfO	36	22	9	9.85
R	LG	16	-90	-4	8.99
L	PC	-42	-53	-33	8.90
L	IFG	-46	18	24	8.63

Supplemental Table 3.1

Alphabetical list of goals used in the scanner

Acing an upcoming exam	Going whale watching
Adopting a pet	Growing a garden
Appearing on TV	Having a better sleep cycle
Applying for jobs after graduation	Having a bonfire
Attending a friend's important event	Having a picnic in a park
Baking a cake	Helping a stranger
Becoming a better cook	Helping as a volunteer
Becoming a better swimmer	Improving your skin

Supplemental Table 3.1 (continued)

Becoming a youth mentor	Improving your wardrobe
Being in a friend's wedding	Investing your money
Buying a car	Joining a student club
Buying a new bike	Keeping a journal
Buying a new laptop	Keeping in touch with a relative
Catching a fish	Keeping up with the news
Cleaning out your room	Learning a foreign language
Cooking a Thanksgiving turkey	Learning a musical instrument
Creating a blog	Learning a new computer program
Donating some blood	Learning how to dance
Eating healthier food	Learning how to paint
Finding a cozy apartment	Learning to do yoga
Finding a great roommate	Learning to drive stick shift
Finding new music you like	Learning to perform CPR
Getting a letter of recommendation	Losing a few pounds
Getting a new phone	Making a photo album
Getting a tattoo	Making breakfast for your parents
Getting a term-time job	Making new friends
Getting an internship	Managing your money better
Getting dinner with an old friend	Meeting a celebrity
Getting in better shape	Performing at a karaoke bar
Getting Lasik surgery	Procrastinating less on school work
Getting new running shoes	Reading for pleasure
Getting to know a professor	Riding a motorcycle
Giving your parents birthday gifts	Seeing a Broadway show
Going apple picking	Sorting out old clothes
Going camping in the forest	Supporting your favorite sports team
Going hiking in the mountains	Swimming with dolphins
Going ice skating	Throwing a surprise party
Going on a cruise	Traveling to a foreign country
Going on a date	Traveling to Paris
Going on a road trip	Visiting a museum
Going on a sailing trip	Visiting family out of state
Going on a ski trip	Visiting your high school teachers
Going on family vacation	Voting for a Presidential candidate
Going scuba diving	Walking/running for charity
Going skydiving with a friend	Watching the NYE ball drop in NYC
Going to a comedy show	Whitening your teeth
Going to a concert	Writing a short story
Going to an amusement park	Writing a song

Supplemental Table 3.2

Peak regions of activation for Odd/Even judgments > Goal simulation

			MNI coordinates			
Lat	Region	BA	*x*	*y*	*z*	BSR
Odd/Even judgments > Goal simulation						
R	pCC	23	6	-32	28	9.17
R	IPL	40	52	-44	50	8.88
R	MFG	8	48	30	46	8.63
R	LG	18	28	-104	-4	8.37
L	INS	3	-40	-2	12	8.14
L	PostCG	2	-54	-24	48	7.63
R	INS	13	42	22	6	7.54
R	CC		18	-50	-26	7.49
L	IOG	18	-30	-98	-14	7.47
R	PCu	7	16	-64	36	7.13
L	MFG	6	-6	0	50	5.76
R	Thal		8	-16	6	5.55
L	CT		-32	-48	-36	5.12
R	CT		16	-62	-52	4.69
L	MFG	8	-30	48	42	4.67
R	Put		18	2	-16	4.17
R	INS	13	42	-16	-8	3.91
R	CT		30	-42	-54	3.88
R	MTG	21	64	-36	-10	3.59
L	CC		-24	-66	-26	3.49
R	STG	38	42	2	-20	3.40
L	CT		-38	-42	-52	3.33
R	IG	37	54	-48	-18	3.04

Note. IOG = Inferior occipital gyrus. Other abbreviations can be found in previous Tables' notes.

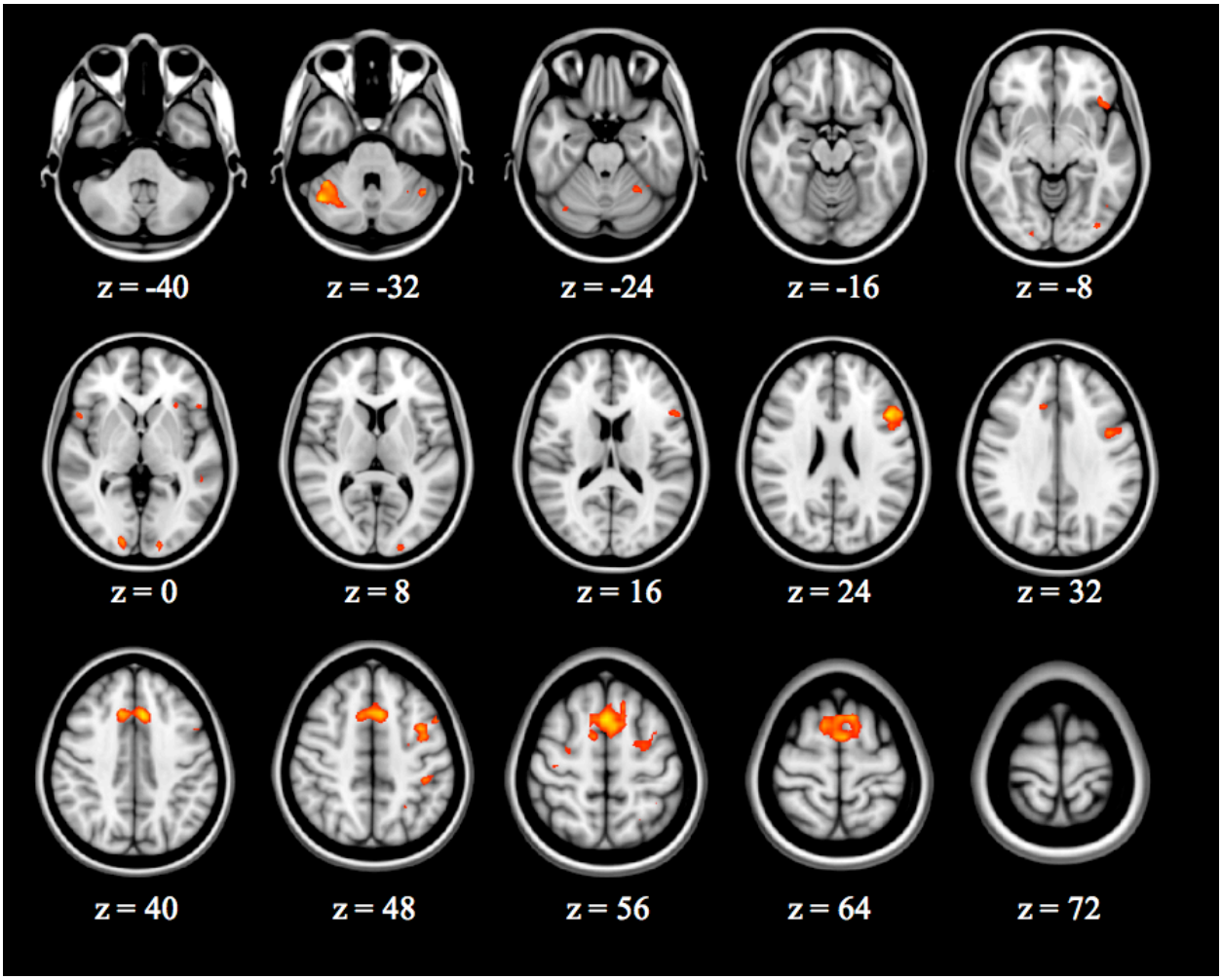
Supplemental Table 4.1

List of actions used in Experiment 2

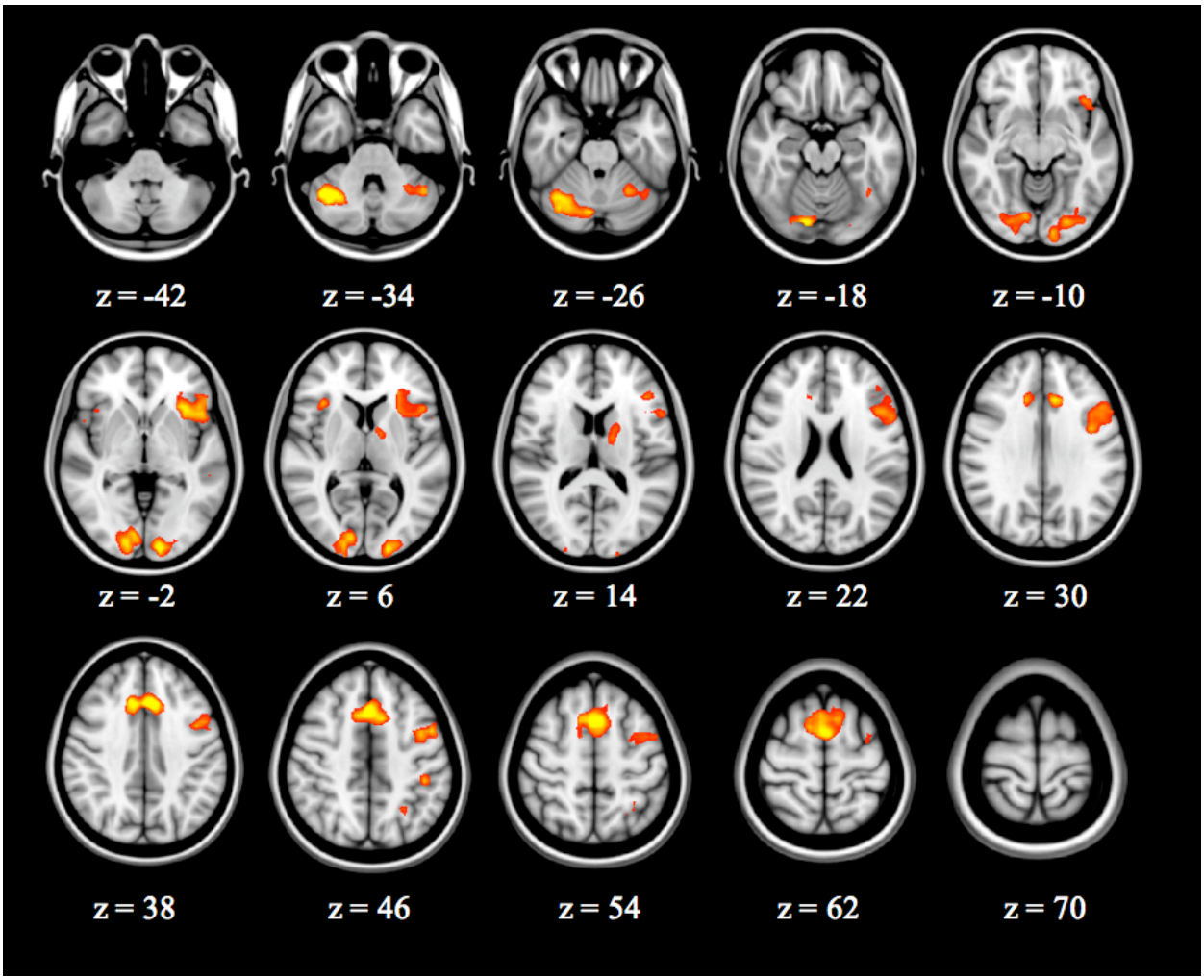
Bounce the ball on the floor	Throw the ball to me
Break the toothpick in two pieces	Break the toothpick in three pieces
Chain the paper clips in a line	Chain the paper clips in a circle
Close the bag	Tear the bag
Color the star in yellow	Color the star in pink
Wipe your nose with the tissue	Tear the tissue
Pick up the green tea bag from the table	Pick up the black tea bag from the table
Draw a circle with the pen	Draw a square with the pen
Put the coin heads up on the table	Put the coin tails up on the table
Pick up the apple	Pick up the orange
Fold the paper towel	Wet the paper towel
Staple two pages with the stapler in the top right	Staple two pages with the stapler in the top middle
Pick up the can of soda	Pick up the bottle of water
Roll the pen on the table	Pick up and put down the pen on the table
Draw a pentagon with the pencil	Draw a triangle with the pencil
Shake the bottle	Pour out the contents out of the bottle
Write your first name on the sticky note	Write your last name on the sticky note
Push the toy car forward	Push the toy car backwards
Put the glove on your right hand	Put the glove on your left hand
Tell me the time on the clock	Tell me the time on the watch
Put the cap on the yellow highlighter	Put the cap on the pink highlighter
Put the card in the envelope	Seal the empty envelope
Pour all the water in cup 1 into cup 2	Pour half the water in cup 1 into cup 2
Tear the paper	Fold the paper in half
Wrap the rubber band around your left wrist	Wrap the rubber band around your right wrist
Blink your eyes	Roll your eyes up
Tell the experimenter what day of the week it is	Tell the experimenter what day of the week two days from now is
"Moo" like a cow	"Baa" like a sheep
Point your index finger to the experimenter	Point your pinky finger to the experimenter
Stick out your tongue	Lick your lips
Wave your hand goodbye	Fan yourself with your hand
Move your head left to right	Move your head up and down
Lift your feet	Move your feet from left to right
Scratch your head	Scratch your arm
Say your name aloud	Say your birthday aloud
Lean backwards in your chair	Lean forward in your chair
Slam your left hand down on the table	Slam your right hand down on the table
Clap your hands together	Snap your fingers

Supplemental Table 4.1 (continued)

Raise your arms	Raise your legs
Tell me the month of the year	Tell me the day of the week
Pretend to laugh	Pretend to cough
Look upward to the ceiling	Look downward to the floor
Point to your mouth	Point to your nose
Spell your last name	Spell your last name backwards
Spell out aloud the word "night"	Spell out aloud the word "day"
Look under the table	Look under your chair
Fold your arms	Cross your legs
Pinch your chin	Pinch your thumb
Rub your stomach	Pat your stomach
Name four colors	Name four animals



Supplemental Figure 2.1. Goal-directed simulation > fixation, $p < .01$, FWE-corrected.



Supplemental Figure 2.2. Semantic association > fixation, $p < .01$, FWE-corrected.